The Need for Fast Near-Term Climate Mitigation to Slow Feedbacks and Avoid Tipping Points

Critical Role of Climate Super Pollutants
To Address the Climate Emergency

Background Note

25 April 2025

Institute for Governance
& Sustainable Development (IGSD)

Center for Human Rights and
Environment (CHRE/CEDHA)

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Institute for Governance & Sustainable Development

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About the Institute for Governance & Sustainable Development (IGSD)

IGSD's mission is to ensure fast cuts to the non-carbon dioxide climate pollutants and other fast climate mitigation strategies to slow near-term global warming and self-amplifying climate feedbacks, avoid or at least delay catastrophic climate and adverse societal tipping points, and limit global temperature to 1.5 °C—or at least keep this temperature guardrail in sight, limit overshoot, and return to a safe temperature as fast as possible.

IGSD's research confirms that decarbonization alone is insufficient to slow near-term warming to keep us below 1.5 °C or even the more dangerous 2 °C guardrail, and that the fastest and most effective strategy is to combine the marathon to zero out carbon dioxide (CO_2) emissions from decarbonizing the energy system *with* the sprint to rapidly cut non-CO_2 super climate pollutants and protect carbon sinks. The super climate pollutants include four short-lived climate pollutants (SLCPs)—methane (CH_4), hydrofluorocarbons (HFCs), black carbon soot, and tropospheric ozone (O_3)—as well as the longer-lived nitrous oxide (N_2O).

Combining the fast mitigation sprint with the decarbonization marathon also helps address the ethical issues of intra-generational equity by giving societies urgently needed time to build resilience and adapt to unavoidable changes. The latest science suggests that the window for exceeding the 1.5 °C guardrail could close as soon as the early 2030s, making this the decisive decade for fast action to slow warming.

The fastest way to reduce near-term warming in the next two decades is to cut SLCPs. Because they only last in the atmosphere from days to 15 years, reducing them will prevent 90 percent of their predicted warming within a decade. Strategies targeting SLCP reductions can avoid four times more warming at 2050 than targeting CO_2 alone. Reducing HFCs can avoid nearly 0.1 °C of warming by 2050 and up to 0.5 °C by the end of the century. The initial HFC phasedown schedule in the Kigali Amendment to the Montreal Protocol will capture about 90 percent of this. Parallel efforts to enhance energy efficiency of air conditioners and other cooling appliances during the HFC phasedown can double the climate benefits at 2050. Cutting methane emissions can avoid nearly 0.3 °C by the 2040s, with the potential for significant avoided warming from emerging technologies to remove atmospheric methane faster than the natural cycle.

Combining the fast mitigation sprint with the decarbonization marathon would reduce the rate of global warming by half from 2030 to 2050, slow the rate of warming a decade or two earlier than decarbonization alone, and make it possible for the world to keep the 1.5 °C guardrail in sight and reduce overshoot. It would also reduce the rate of Arctic warming by two-thirds. This would help slow self-amplifying climate feedbacks in the Arctic, and thus avoid or at least delay the cluster of projected tipping points beyond 1.5 °C. Reducing climate risks and staying within the limits to adaptation are critical to building resilience.

IGSD's approach to fast mitigation includes science, technology, law and policy, and climate finance. IGSD works at the global, regional, national, and subnational levels.

About the Center for Human Rights and Environment (CHRE/CEDHA)

Originally founded in 1999 in Argentina, the Center for Human Rights and Environment (CHRE or *CEDHA by its Spanish acronym*) aims to build a more harmonious relationship between the environment and people. Its work centers on promoting greater access to justice and to guarantee human rights for victims of environmental degradation due to the non-sustainable management of natural resources, and to prevent future violations. To this end, CHRE fosters the creation of public policy that promotes inclusive socially and environmentally sustainable development, through community participation, public interest litigation, strengthening democratic institutions, and the capacity building of key actors.

CHRE addresses environmental policy and human rights impacts in the context of climate change through numerous advocacy programs including initiatives to promote fast action climate mitigation policies to contain and reverse climate change; to reduce emissions of short-lived climate pollutants such as black carbon, HFCs, and methane; and to protect glaciers and permafrost environments for their value as natural water storage and basin regulators, to avoid their melt impacts on sea level and subsequent influence on ocean currents and air streams, as well as for their global albedo value and for the many other roles glaciers play in sustaining planetary ecological equilibrium. CHRE also fosters corporate accountability and human rights compliance to address the social and environmental impacts of key climate polluting industries such as oil and gas (including hydraulic fracturing), mining, paper pulp mills, and artisanal brick production.

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Critical Role of Climate Super Pollutants to Address the Climate Emergency

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1. Introduction and summary

This *Background Note* summarizes the science supporting the need for fast climate mitigation to slow warming in the near term (from now to the 2040s) as a necessary complement to zeroing out CO_2 emissions through decarbonization. This dual strategy is essential for addressing the climate emergency. It focuses on the importance of cutting climate super pollutants and protecting carbon sinks as the most effective ways to slow self-amplifying feedbacks, and to avoid, or at least delay, irreversible tipping points and the existential risk these present to ecosystems and human societies. Climate super pollutants are warming agents that are far more potent than carbon dioxide (CO_2) per ton. They include long-lived greenhouse gases like nitrous oxide and SF_6, as well as short-lived climate pollutants (SLCPs) methane (CH_4), tropospheric ozone (O_3), hydrofluorocarbons (HFCs), and black carbon.

- "The mitigation potential of the SP [super pollutant] lever with a maximum deployment of current technologies … is about 0.6 °C by 2050 and 1.2 °C by 2100…."[1]
- In contrast, decarbonization on its own avoids only a modest 0.1 °C of warming by 2050.[2] This is because the cooling sulfates, which are co-emitted with fossil fuel combustion, fall out of the atmosphere quickly when a fossil fuel source is shut down. This "unmasks" current warming from CO_2.
- When decarbonization is combined with fast mitigation of super pollutants, this avoids four times more warming at 2050 than decarbonization on its own.[3]
- Cutting the climate super pollutants also reduces projected warming in the Arctic by two-thirds and cuts the rate of global warming by half.[4]

The *Background Note* describes the climate emergency as two challenges, or races, that must be run and won simultaneously: the *marathon* to decarbonize the fossil fuel economy by 2050 or earlier and stabilize the climate in the longer term, and the *sprint* to cut SLCPs and reduce the rate of warming in the near term.

- Winning the super pollutant sprint is the only known strategy for slowing near-term warming fast enough to slow self-amplifying climate feedbacks and to avoid, or at least delay, a cascade of irreversible tipping points.
  - The first five irreversible tipping points are anticipated past the 1.5 °C guardrail of the Paris Agreement,[5] a temperature exceeded in 2024, at least temporarily, and which is on course to be locked in for the long-term by 2030.[6]
- Winning the super pollutant sprint also is essential for building resilience and staying within the limits of adaptation.[7]

A. The window is closing for keeping within a safe climate zone

The window for addressing the climate emergency is shrinking to perhaps 10 years or less. The rate of warming has increased in the past few years,[8] and it is all but inevitable that we'll break through the 1.5 °C guardrail of the Paris Agreement.[9] This requires an urgent course correction. The climate emergency is a problem of *temperature*, *time*, and *tipping points.*

- The *temperature* of Earth is already too hot: 2024 marked the first time global temperatures breached 1.5 °C for an entire calendar year (**Appendix A, Box 1**).[10] Temperatures in early 2025 remain above 1.5 °C.[11]
- Many planetary vital signs—including ocean heat content, sea level rise, and forest cover lost to fires—are at record highs,[12] and six of nine planetary boundaries have been transgressed.[13]
- Given our current emissions trajectory, the probability and impacts of extreme record-breaking heatwaves will continue to increase with each increment of additional warming (**Appendix B, Box 2**).[14]
- Because extreme climate impacts depend on the *rate of warming* as well as the *total warming*, the sustained rate of increases in CO_2—accompanied by continued emissions of methane and other climate pollutants—is particularly dangerous.[15]
- The rate of CO_2 concentrations in the atmosphere is currently increasing at least 10 times faster than at any other time during the last 800,000 years,[16] driven by continuing emissions and an apparent slowing of the ocean and terrestrial sinks,[17] which typically take up 50% of CO_2 emissions (**Appendix C**).[18]
- Today, the blanket of climate pollution surrounding the Earth is trapping nearly twice as much heat as it did in 2005.[19] Climate feedbacks such as "[m]arked decreases in clouds and sea ice" are also contributing to the extra heat the planet is now retaining.[20]

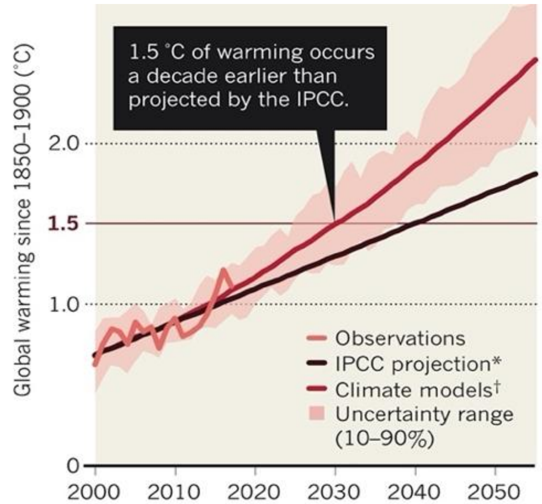
Box 1. Types of temperature and warming as defined by the Intergovernmental Panel on Climate Change (IPCC)

Daily, monthly, and even yearly temperatures above 1.5 °C do not mean that we have breached the Paris Agreement guardrail. This is because the IPCC and others apply different definitions of temperature to different timeframes and contexts. These include:[21]

- The observed global average *annual temperature* is a single year of temperature conditions, averaged over the planet. It varies year-to-year due to internal variability and weather patterns, such as the El Niño Southern Oscillation.
- *Current total warming* is the observed change in annual temperature averaged over the preceding 10 or 20 years. It includes both natural and anthropogenic components, but using a longer period reduces year-to-year fluctuations in temperature and allows for a better understanding of the overall warming trend.
- Under the practice of the IPCC, reaching *the long-term level of global warming* can be confirmed at the midpoint of the first 20-year period when average global surface air temperature change exceeds a particular level of warming.[22]
    - Model projections that take into account the record warmth of 2023 and 2024 anticipate that the long-term 1.5 °C level of warming will be locked-in by 2030 or sooner.[23] However, because the IPCC uses a 20-year observational record to confirm the global warming level, the IPCC cannot confirm that the Paris guardrail has been exceeded until another decade has passed after the midpoint (*i.e.*, 2040).[24]

According to climate scientist James Hansen, "The 1.5 degree limit is deader than a doornail,"[25] and the 2 °C upper guardrail is in jeopardy if emissions keep rising.[26] Further information on this topic is provided in **Appendix A**.

Figure 1. Projected warming



Source: Xu Y., Ramanathan V., & Victor D. (2018) [*Global warming will happen faster than we think*](), Comment, NATURE 564: 30–32.

- The *rate* of warming increased from the 0.2 °C per decade trend of the past 40 years to at least 0.25 °C per decade between 2014–2023 (**Figure 1**).[27]
- Exceeding the 1.5 °C guardrail will compound global warming's already severe effects, heightening risks of triggering self-amplifying *feedback loops* and of passing Earth system *tipping points*, which can have non-linear and potentially catastrophic impacts.[28]

B. Cutting CO_2 alone does not slow near-term warming, but cutting SLCPs does

Reducing short-lived climate pollutants (SLCPs) is the only currently known way to cut the rate of warming in the near-term, slow self-reinforcing feedbacks, and avoid, or at least delay, irreversible tipping points. In addition to zeroing out CO_2 emissions to curb long-term warming, it is essential to slow near-term warming by reducing short-lived climate pollutants—methane (CH_4), black carbon (BC) soot, tropospheric ozone (O_3), and hydrofluorocarbons (HFC). (These short-lived pollutants are often referred to as *climate super pollutants* because of their potency and ability to quickly reduce warming. N_2O is also a super pollutant but is not short-lived.)

- The CO_2 and super climate pollutant strategies are complementary and not exchangeable. Achieving the 2050 net zero CO_2 targets is essential for stabilizing the climate by the end of the century, due to the long lifetime of CO_2 in the atmosphere; but it cannot, by itself, prevent global temperatures from exceeding 1.5 °C above pre-industrial levels (**Section 2**).
  - The Intergovernmental Panel on Climate Change (IPCC) 6th Assessment Report (AR6) confirms that cutting fossil fuel emissions—the main source of CO_2—by decarbonizing the energy system and shifting to clean energy, *in isolation, actually makes global warming worse in the short term*. This is because burning fossil fuels also creates sulfate (SO_2) aerosols, which act to cool the climate. These cooling sulfates fall out of the atmosphere fast, while CO_2 lasts much longer—decades to centuries—thus leading to relatively higher warming for the first decade or two.[29]
  - The International Energy Agency (IEA) report, [*Credible Pathways to 1.5 °C: Four Pillars for Action in the 2020s*](), also recognizes that taking action on non-CO_2

emissions is needed to limit peak warming. Aggressive decarbonization, faster phasedown of HFCs under the Kigali Amendment, and cuts to methane in line with the Global Methane Pledge all "could make the difference between a scenario which substantially overshoots 1.5 °C" and one that does not.[30]

- According to AR6 Working Group III (WGIII) Summary for Policymakers, keeping the planet livable by limiting warming to 1.5 °C (with no or limited overshoot) requires reducing human-caused CH_4 emissions by 34% in 2030 and 44% in 2040, relative to modelled 2019 levels.[31] In addition, global CO_2 emissions must be reduced by nearly half in 2030 and by 80% in 2040,[32] along with deep cuts to other SLCPs and nitrous oxide (N_2O).[33]

Box 2. Extreme weather impacts are too severe today where long-term warming is 1.2 °C

Flooding

- Over the past 20 years, rising sea levels have exposed 14 million more people around the world to one-in-20-year coastal flooding.[34]
- In 2022, the catastrophic flooding that affected 33 million people in Pakistan[35] was very likely made more severe by climate change, increasing rainfall, glacier melt, and the persistence of the La Niña event in the Pacific for a rare third year.[36]

Droughts

- Since 2010, Chile has been in megadrought, the longest and most severe drought in the country in over a thousand years.[37] Drought conditions (along with an El Niño year) increased the favorability of fire weather during Chile's 2023 fire season.[38]
- The Amazon River Basin drought that began in 2023 and continued into 2024 was made 10–30 times more likely by climate change. If the planet warms to 2 °C, such a drought could occur every 10–15 years.[39]
- In the U.S. West, warming-driven snow loss may reduce spring snowpack runoff by 30–40% by 2100, with consequences for water scarcity in populous river basins.[40]

Storms & Cyclones

- Hotter oceans are fueling more intense and destructive tropical storms. The 2024 Atlantic hurricane season was the ninth consecutive year with an above-average number of storms,[41] with climate change intensifying rainfall and winds from Hurricanes Milton and Helene.[42] Three back-to-back major typhoons made landfall in the Philippines, affecting 13 million people.[43]

Extreme Heat

- Extreme heat is becoming normalized in today's world. Heatwaves that would have occurred only once every 10 or 50 years in the climate of 2000 are now striking four times more often.[44]
- Dangerous heat disproportionately impacts the most vulnerable. In 2024, people living in Small Island Developing States experienced about three times more days of risky heat from global warming than the average person who lived elsewhere.[45]
- Between May 2023 to May 2024, 78% of the world's population (6.3 billion people) endured at least one month's worth of extreme heat that was made at least two times more likely by global warming.[46]

For more information on current and future extreme heat impacts, see **Appendix B**.

- If CO_2 emissions continue at 2024 levels, the ~235 $GtCO_2$ remaining in the global carbon budget for a 50% chance of keeping temperature rise limited to 1.5 °C will run out in six years or less.[47]
- While the carbon budget only directly measures the amount of CO_2, the budget calculation assumes significant reductions of CH_4 (~50%), N_2O (~20%), and cooling SO_2 aerosols (~80%) between 2020–2050.[48]
    - Failing to reduce non-CO_2 emissions below these levels continues to shrink the remaining carbon budget.[49]
    - While this budget includes some climate feedbacks from the carbon cycle,[50] given the uncertainty around the timing and likelihood of tipping points, the carbon budget accounting method may produce over-optimistic estimates.[51]
    - Indeed, if feedbacks from permafrost thaw and forest die-off are included, "the remaining budget could be all but erased already."[52]
- The targets set out in Nationally Determined Contributions (NDCs) under the Paris Agreement, which many countries are failing to meet,[53] are insufficient to limit warming to the 1.5 °C guardrail. Even if NDCs are achieved, the planet will reach 2.6 °C [1.8–3.4 °C] of peak warming this century,[54] substantially magnifying the risk that we will trigger Earth system tipping points.[55]

C. Only a combined CO_2 + super pollutant strategy can address the climate emergency to avoid climate catastrophe and tipping points

- Addressing the near-term climate emergency requires selecting fast mitigation solutions that provide the most avoided warming in the shortest period over the next decade or two,[56] slow the rate of warming, and protect the most vulnerable people and ecosystems from heat, drought, flooding, and other extremes.[57]
    - In addition to cutting CO_2 and super climate pollutants (**Section 3**), it is critical to protect carbon sinks, another fast mitigation strategy (**Section 4**).[58]
- These fast mitigation strategies are needed to slow self-amplifying feedbacks, like permafrost thaw or loss of Arctic summer sea ice,[59] and avoid or at least delay irreversible tipping points that can cause the Earth to warm itself (**Section 5**).[60]
    - Exceeding 1.5 °C increases the likelihood of triggering or committing to the first five of 16 climate tipping points: melting the Greenland Ice Sheet and the West Antarctic Ice Sheet, thawing boreal permafrost, losing low-latitude coral reefs, and losing reflective Barents Sea ice in the Arctic.[61]
    - At 2 °C of warming, the risks of triggering "relatively large, abrupt and sometimes irreversible changes in systems" become high.[62]
    - According to the *2023 Global Tipping Points Report*, several tipping points "are no longer high-impact, low-likelihood events, [but] are rapidly becoming high-impact, high-likelihood events."[63] Early warning signals indicate that the Greenland Ice Sheet, Amazon rainforest, and Atlantic Meridional Overturning Circulation are approaching tipping.[64]
    - Self-amplifying climate feedback loops can accelerate warming and increase the risk of triggering tipping points, propelling a part of the climate system over a cliff, and potentially setting off a cascade of tipping points that fall like dominoes.[65]

- The findings presented in this introduction build on the conclusions of the IPCC's 2018 *Special Report on Global Warming of 1.5 °C*, which identified the three strategies essential to keep the planet livable:
  - Reaching net zero CO_2 by mid-century.
  - Making deep cuts to super climate pollutants in the next decades.
  - Removing up to 1,000 billion tons of CO_2 from the atmosphere by 2100.[66]

2. Cutting CO_2 alone will not slow warming in the near term

Decarbonizing the energy system and achieving net zero emissions is critical for stabilizing the climate and limiting temperatures to 1.5 °C by the end of this century. However, transitioning from fossil energy could, paradoxically, increase or "unmask" warming over the next two decades. Burning fossil fuels rich in sulfur, such as coal and diesel, releases sulfate aerosols along with greenhouse gases (GHGs). Sulfate aerosols scatter sunlight to cool the planet and currently hide about 0.5 °C of global warming,[67] masking the full extent of human-caused climate change.

Unlike CO_2, which can stay in the atmosphere for centuries, cooling sulfate aerosols disappear from the atmosphere within days or weeks. Cutting fossil fuel use will cause sulfate aerosols—and their cooling effect—to vanish quickly, but it will take decades or longer for the heat-trapping blanket of CO_2 around the planet to thin. Between now and 2050, unmasking could temporarily increase or even speed up warming as fossil fuel sources and the cooling aerosols they emit are eliminated.[68] One study calculated that cuts to fossil CO_2 emissions and associated reductions in cooling aerosols could cause 0.02–0.10 °C of warming over the next two decades.[69] However, as sulfate aerosols are also harmful air pollutants, reducing them provides a long-term health benefit.

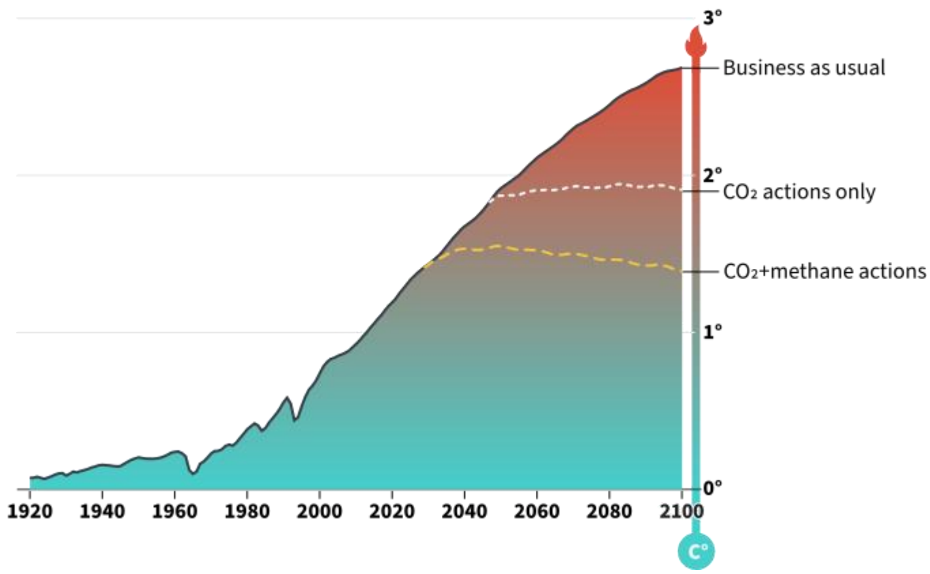
The only practical way to counteract unmasking is by cutting the fast-acting climate super pollutants, particularly methane.[70]

- Historical evidence indicates that sulfate aerosols can effectively mask warming at the regional and global level.
  - The 1991 Mount Pinatubo eruption demonstrated the temporary cooling effects of aerosols. By injecting 15 million tons of sulfur dioxide (SO_2) into the atmosphere, the eruption temporarily cooled the planet by 0.5 °C for nearly two years.[71]
  - The potential speed and magnitude of unmasking was observed during the pandemic shutdown. The abrupt reduction of fossil fuel burning resulted in temporary unmasking over South Asia, which increased local radiative forcing by 1.4 Wm^{-2}, equivalent to three-fourths of radiative forcing from all CO_2.[72]
- Since the late 20th century, levels of sulfates and other aerosols in the atmosphere have declined, in response to national air pollution. Satellite data and climate models indicate that these changes are already impacting the amount of heat that the planet traps.
  - Over the last two decades, the loss of some sulfate cooling strengthened the greenhouse effect by up to half as much as increasing levels of CO_2 did. Researchers have concluded "[t]his signal will most likely continue in the future, increasing the urgency for strong measures on reducing greenhouse gas emissions[.]"[73]
  - Reductions in aerosol emissions over 2001–2019 doubled the rate at which the atmosphere gained more energy than it could emit.[74] The International Maritime

Organization's (IMO) 2020 restrictions on shipping fuels, aimed at reducing aerosol pollution, may be adding to this trend.[75]

- As countries in South and East Asia work to alleviate air pollution over the next two decades, aerosol reductions could drive hotter seasonal extremes in the region, according to climate models.[76]

Figure 2. Avoided warming from simultaneous mitigation of CO_2 and methane compared with CO_2-only mitigation



Source: Reproduced from Gordon D., Irakulis-Loitxate I., & Dreyfus G. (17 September 2024) *Two Carbon Co-Conspirators Need to Be Stopped to Tackle Climate Change*, RMI, using modeled data from Reisinger A. (2024) *Why addressing methane emissions is a non-negotiable part of effective climate policy*, FRONT. SCI. 2: 1–5.

3. Cutting short-lived climate super pollutants is the only way to slow warming in the near term

Aggressive mitigation of short-lived climate pollutants (SLCPs)—methane, tropospheric ozone, black carbon, and HFCs—is critical for near- and long-term climate protection. These SLCPs are known as *climate super pollutants*, because of their potency and ability to quickly reduce warming. Nitrous oxide, N_2O, is also a super climate pollutant but is not short-lived.

The AR6 WGI (Working Group I) chapter on short-lived climate pollutants noted that "[s]ustained methane mitigation, wherever it occurs, stands out as an option that combines near- and long-term gains on surface temperature (*high confidence*) and leads to air quality benefits by reducing surface ozone levels globally (*high confidence*). Additional CH_4 and BC [black carbon] mitigation would contribute to offsetting the additional warming associated with SO_2 reductions that would accompany decarbonization (*high confidence*)."[77] The AR6 Synthesis Report further affirmed that "[s]trong, rapid and sustained reductions in methane emissions can limit near-term warming and improve air quality by reducing global surface ozone (*high confidence*)."[78]

Cutting SLCPs is the only plausible way to limit warming due to unmasking of cooling aerosols over the next 20 years.[79]

- Accounting for the co-emission of cooling aerosol from fossil fuel burning, a 2022 study found that strategies focusing exclusively on reducing fossil fuel emissions could result in "weak, near-term warming," which could potentially cause temperatures to exceed the 1.5 °C level by 2035 and the 2 °C level by 2050.
  - When accounting for unmasking, policies targeting CO_2 through phasing out fossil fuel use would avoid net warming of about 0.07 °C by 2050 compared with 0.26 °C avoided net warming from measures targeting SLCPs.[80]
  - Further, the dual strategy that pairs CO_2-focused decarbonization with rapid reductions to the non-CO_2 pollutants, especially the SLCPs, would result in net avoided warming by 2050 of about 0.34 °C.[81] This is more than four times larger than the net effect of decarbonization alone, which would enable the world to stay well below the 2 °C limit and significantly improve the chance of keeping temperature rise limited to the 1.5 °C guardrail.[82]
  - Another study found deep cuts to SLCPs and N_2O, coupled with aggressive decarbonization, can reduce the rate of warming before 2040.[83]

Figure 3. Temperature response of mitigation strategies focusing only on CO_2 (decarbonization alone) compared to decarbonization plus measures targeting super climate pollutants

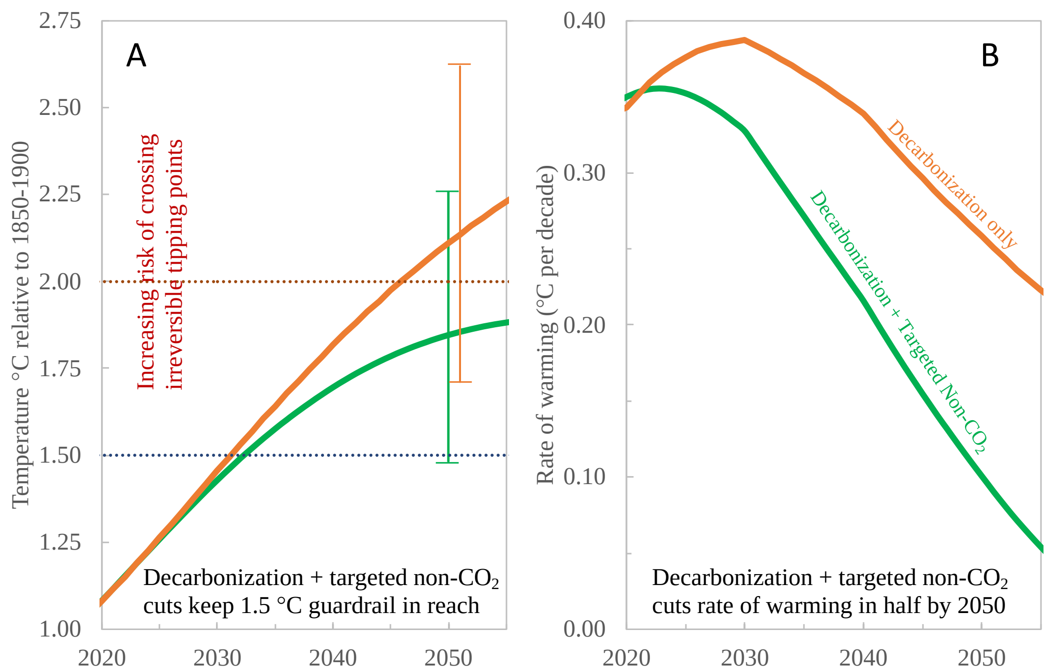


Figure A: Global Surface Air Temperature relative to pre-industrial for two scenarios: decarbonization alone (orange) and decarbonization plus measures targeting non-CO_2 pollutants including methane, hydrofluorocarbon refrigerants, black carbon soot, ground-level ozone smog, as well as nitrous oxide (green). Vertical lines illustrate range adapted from inter-model spread (5% to 95%) for scenario SSP1-1.9 from IPCC AR6 WGI Figure SPM.8a. *See* Intergovernmental Panel on Climate Change (2021) *Summary for Policymakers*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.) (Figure SPM.8a).

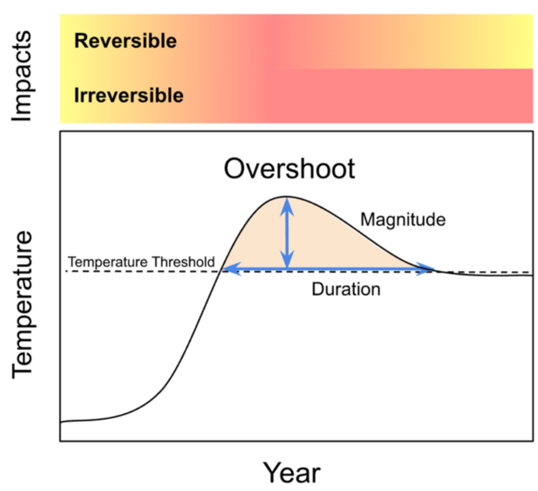
Figure B: Rate of warming per decade for each scenario. *Adapted from* Dreyfus G. B., Xu Y., Shindell D. T., Zaelke D., & Ramanathan V. (2022) *Mitigating climate disruption in time: A self-consistent approach for avoiding both near-term and long-term global warming*, PROC. NAT'L. ACAD. SCI. 119(22).

- Reducing HFCs through the 2016 Kigali Amendment to the Montreal Protocol will account for nearly 0.1 °C of the avoided warming by 2050.[84]
- SLCP reductions slowed warming in the past. During the warming slowdown of 1998–2012, temperatures still increased, but they did so at a slower rate than in previous decades, even as CO_2 emissions kept growing. The phaseout of ozone-depleting substances under the Montreal Protocol and the slower growth rate of methane during this time offset about 25% of the warming caused by other climate pollutants (including CO_2).[85]
- Scientists have repeatedly emphasized the importance of urgently cutting SLCPs to avoid dangerous feedback loops and tipping points: in the 2019 warning of the climate emergency, co-signed by 11,000 scientists;[86] in subsequent annual updates to the climate indicators assessed in the warning;[87] as well as in the *2023 Global Tipping Points Report*.[88]
    - Above 1.5 °C, every additional 0.1 °C of warming raises the risk of passing tipping points.[89] Keeping tipping risks low therefore requires an end-of-century global temperature of 1.5 °C and minimizing temporary overshoot (**Box 3**).**Error! Reference source not found.**[90] Most achievable pathways to reach this goal require rapid, deep, and sustained reductions in SLCPs, in addition to zeroing out emissions of CO_2 (and other long-lived greenhouse gases like N_2O) by mid-century.[91]

Box 3. Understanding overshoot: reversible and irreversible risks

In this *Note,* overshoot refers to instances when the global average temperature temporarily exceeds the Paris Agreement guardrail of 1.5 °C. The IPCC set an implicit goal of "no or limited overshoot,"[92] but poorly defined the boundaries of overshoot *magnitude* and *duration* (blue lines in **Figure 4**).[93] While risk assessments exist for peak warming levels, the latest science has yet to specify the risks and impacts associated with other overshoot features, such as overshoot duration or the *cumulative degree-years* of overshoot (orange area in **Figure 4**).[94] Some of the damages may be irreversible, despite the assumption that overshoot will be temporary (compare the reversible and irreversible ember bars at top of **Figure 4**).[95] Irreversible impacts include extra sea level rise from committed ice sheet melt, which would occur over the course of millennia but could be triggered by an overshoot of much shorter duration.[96] Regional impacts from overshoot may be hard to predict if projections only look at global temperatures.[97]

Figure 4. Illustration of overshoot and types of impacts



Even with clearer constraints on overshoot, the notion that overshoot will be temporary is a dangerous assumption based on largely theoretical carbon dioxide removal (CDR) technologies.[98] Avoiding or limiting overshoot in the first place is therefore a safer bet than reducing overshoot after-the-fact.[99] Immediate action on super pollutants, especially methane, is our primary emergency brake.[100]

A. Methane (CH_4)

Cutting methane emissions is the biggest and fastest strategy for slowing warming and keeping the limit of 1.5 °C temperature rise within reach.[101] Pricing and reducing methane, alongside decarbonization, is critical to slow near-term warming, minimize the risks of passing dangerous tipping points, and limit extreme climate impacts.[102]

Contribution to global warming

- Methane emissions from human activity are responsible for nearly 45% of current net warming.[103]
- According to AR6 WGI, methane pollution has already caused 0.51 °C of warming of the total observed warming for 2010–2019 of 1.06 °C (0.88–1.21 °C).[104]
- Warming caused by methane will continue to increase as anthropogenic and natural methane emissions grow (**Appendix C**).[105] Atmospheric concentrations of methane are now two-and-a-half times greater than pre-industrial levels,[106] and methane emissions from human activities in 2023 alone "will cause around the same amount of warming over the next 10 years" as a single year's worth of CO_2 emissions from fossil fuels.[107]
- Methane also is an indirect climate forcer as a precursor to other GHGs, notably tropospheric ozone; it also reduces the formation of cooling sulfate aerosols by acting as a sink for the hydroxyl radical.[108]

Sources

- Humans are responsible for about two-thirds of methane emissions.[109] This includes methane emitted as a result of human transformation of wetlands and inland freshwaters, in addition to methane from the fossil fuel, agriculture, and waste sectors.[110] For the first time, the 2024 Global Methane Budget attributed these human-enhanced methane emissions from natural systems to their anthropogenic sources. This increases the share of methane emissions attributed to human activity when compared with the 2020 Global Methane Budget.[111]
- Both human and natural methane emissions have contributed to the increase in atmospheric methane since 2007.[112] Human and natural emissions contributed to the recent annual growth rate spike between 2020–2022, and continued large annual increases since.[113]
- Separating out the natural and anthropogenic contributions to the recent surges is complicated by limitations in observations and models of natural emissions processes; uncertainties in anthropogenic emissions; and uncertainties in possible changes in methane sinks, which occur primarily through the reaction with the hydroxyl (OH) radical.[114]
- Recent studies identified feedback mechanisms from natural sources and sinks, which accelerated the growth of methane in 2020 and 2021. Natural methane sources appear to be emitting more in response to warmer and wetter conditions associated with climate change.[115]
    - Future projections of human-magnified natural methane emissions from this warmer and wetter world are underestimated or excluded in IPCC scenarios.[116] Reduced methane removal by the atmosphere, due to less hydroxyl radical (OH) available during the pandemic shutdowns, also appears to have contributed to the recent surge.[117]

- Over the 2020–2022 period, the amount of methane in the atmosphere increased 1.5–2.5 times faster than model averages projected, which indicates that "policies may have to be even stronger than those in existing analyses to reach the Paris Agreement's goals."[118]

Table 1. Methane mitigation potential in 2030 by sector in MtCH$_4$/yr and Mt/yr of CO$_2$e

	Mt CH$_4$/yr	Mt CO$_2$e/yr [GWP$_{100}$]	Mt CO$_2$e/yr [GWP$_{20}$]
Oil & gas	29–57	812–1,596	2,436–4,788
Waste	29–36	812–1,008	2,436–3,024
Agriculture	10–51	280–1,428	2,840–4,284
Coal	12–25	336–700	1,008–2,100

Source: United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*.

Global Methane Assessment

- The 2021 *Global Methane Assessment* (GMA) from the Climate and Clean Air Coalition (CCAC) and United Nations Environment Programme (UNEP) led by Dr. Drew Shindell concludes that available mitigation measures could reduce human-caused methane emissions by 45% by 2030, relative to projected increasing baseline emissions in 2030,[119] and avoid nearly 0.3 °C of warming by the 2040s (**Figure 5**).[120]
  - This would prevent 255,000 premature deaths (not including additional benefits of preventing approximately 200,000 premature ozone-related deaths per year), 775,000 asthma-related hospital visits, 73 billion hours of lost labour from extreme heat, and 26 million tons of crop losses globally (annual value beginning in 2030).[121] Each ton of methane reduced generates US$4,300 in health, productivity, and other benefits.[122] In addition, methane mitigation strategies provide further cost reductions and efficiency gains in the private sector, create jobs, and stimulate technological innovation.
  - Roughly 60% of available targeted measures have low mitigation costs (defined as less than US$21 per ton of CO$_2$e for GWP$_{100}$ and US$7 per ton of CO$_2$e for GWP$_{20}$), and just over 50% of those have negative costs.
  - In the IEA net zero emissions by 2050 scenario, total methane emissions from human activity are reduced by 45% and the energy sector by 75% between 2020 and 2030, at a cost of less than 3% of net income from oil and gas in 2022.[123]
- As the GMA notes, "any action taken to reduce emissions will have an immediate pay off for climate in addition to the current and near-future human health and agricultural production. … Indeed, the expectation that a reduction in emissions will yield quick results, in the order of a decade, is confirmed and emphasizes the importance of methane."[124]
- Fast action to pursue all available methane mitigation measures now could slow the global rate of warming by 30% by mid-century.[125] This is consistent with the 2011 UNEP/World Meteorological Organization (WMO) Assessment showing that fully implementing measures targeting methane and black carbon could halve the rate of global warming and reduce Arctic warming by two-thirds.[126]
  - Strategies to cut methane emissions achieve 60% more avoided warming in the Arctic than the global average, with the potential to avoid 0.5 °C by 2050.[127]

  - Rapid reductions in methane emissions also reduces the risk of losing all of the reflective summer Arctic sea ice.[128]
- Methane mitigation before 2030, along with stringent CO_2 mitigation, can keep global warming well below 2 °C over the next 300 years.[129]
  - Every 10-year delay in methane mitigation after 2040 would cause further peak warming of around 0.1 °C, and would further amplify surface air temperature levels due to biogeochemical feedbacks.[130]
- AR6 WGII and WGIII confirm the findings of the GMA that "[s]ustained methane mitigation, wherever it occurs, stands out as an option that combines near- and long-term gains on surface temperature (*high confidence*) and leads to air quality benefits by reducing surface ozone levels globally (*high confidence*)." Measures specifically targeting methane are essential, as broader decarbonization measures can only achieve 30% of the needed reductions.[131]
  - The most recent report on climate solutions, AR6 WGIII, reinforces the conclusion that deep and rapid cuts to methane emissions are essential to limiting warming in the near-term and shaving peak warming from overshooting 1.5 °C.[132] Limiting warming to 1.5 °C with little or no overshoot requires reducing emissions by 34% below 2019 levels in 2030 and 44% below 2019 levels in 2040.[133]
- Although deep reductions to methane are "non-negotiable" to keep warming within the guardrails of the Paris Agreement, [134] only 13% of global methane emissions are covered by existing policy targets as of 2024.[135]
  - A 2024 analysis by Shindell (a leader of the Global Methane Assessment) estimated that delaying methane reductions until 2040 would lead to an additional 8.8 million premature deaths due to ozone exposure by 2050, as well as US$315 billion in damages from lost outdoor labor.[136]

Mitigation and removal

- Anthropogenic emissions, which make up over 60% of total global methane emissions,[137] come primarily from three sectors: energy production (~35%), agriculture (~40%), and waste (~20%).[138] Currently available mitigation measures could reduce emissions from these major sectors by about 180 million metric tons of methane per year (Mt CH_4/yr), approximately 45%, by 2030 relative to projected baseline emissions in 2030.[139]
- Specific measures to reduce methane emissions include:
  - Strengthening methane mitigation policies by implementing readily available technologies, laws, and governance structures to their fullest, and considering ways to expand methane mitigation through other available avenues;[140]
  - Reducing leaks[141] and venting[142] in the oil and gas sector. The Clean Air Task Force states that prohibiting venting of natural gas can reduce emissions by 95%;[143]
  - Eliminating flaring from oil and gas operations, while shifting to clean energy.[144]
  - Improving feeding and manure management on farms. In the U.S., this could cut emissions from manure by as much as 70% and emissions from enteric fermentation by 30%;[145]
  - Eliminating gas in new construction and phasing out leaky gas stoves;[146]
  - Upgrading solid waste and wastewater treatment;[147] and

    - Reducing food waste, diverting organic waste from landfills, and improving landfill management, which could reduce landfill emissions in the U.S. by 50% by 2030 and help close the dietary nutrient gap and improve global food security.[148]
- There is research underway on the best approach for removing atmospheric methane.[149] This is especially important as 35–50% of methane emissions are from natural sources, for which no mitigation options are currently available.[150] Methane removal is discussed further in **Section 4A**.

Global Methane Pledge

- The Global Methane Pledge launched at COP26 in November 2021 under the leadership of the United States and the European Union.[151] The voluntary Pledge commits governments to a collective goal of reducing global methane emissions by *at least* 30% below 2020 levels by 2030 while moving towards the highest-tier IPCC good practice inventory methodologies to quantify methane emissions, with a particular focus on high emission sources. As of COP29 in 2024, the Pledge has mobilized over US$2 billion in loans and grants to support methane mitigation.[152] Funds to support methane reduction efforts are being distributed through the Global Methane Hub,[153] which has regranted US$203 million to over 132 organizations since 2021.[154]
    - As of April 2025, 159 countries and the EU have joined the Pledge,[155] representing over 70% of the global economy[156] and over half of anthropogenic emissions.[157]
    - Successful implementation of the Pledge would reduce warming by at least 0.2 °C by 2050,[158] and would keep the planet on a pathway consistent with staying within 1.5 °C.[159] This reduction is roughly equivalent to a reduction of 36% below projected 2030 levels.[160] Deploying all available and additional measures, as described in the Global Methane Assessment, could lead to a 45% reduction below 2030 levels to achieve nearly 0.3 °C in avoided warming by the 2040s.[161]
    - Implementing the Pledge would provide additional benefits, including preventing ~200,000 premature ozone-related deaths each year, avoiding ~580 million tons of yield losses of staple crops like rice and maize annually, avoiding ~US$500 billion annually in losses due to non-mortality health impacts, as well as impacts on forestry and agriculture, and avoiding ~1,600 billion hours of work lost annually due to heat exposure.[162] Nearly 85% of targeted measures have benefits that outweigh net costs.[163]
    - A progress report from Karryos on the performance of several Pledge signatories found that, as of the middle of 2024, their total methane emissions continue to rise.[164] However, the intensity of methane emissions fell in the U.S.,[165] suggesting that at least some of the domestic policies put in place following the Pledge are beginning to have an impact.

Box 4. Time and temperature methane metrics: GWP_{20} is an improvement, temperature is even better!

Reducing the risks associated with accelerating warming requires mitigation strategies, like cutting methane emissions, that can slow warming in the near term. Assessing how strategies affect near-term warming requires considering individual emissions by pollutant in units of mass, as required under United Nations Framework Convention on Climate Change (UNFCCC) reporting guidelines and recommended by climate scientists.[166] It also requires accounting for co-emissions by source, since policies act on sources, not on individual pollutants.

An ideal option for assessing temperature impact is to convert emissions by source in terms of pollutant and co-emissions to temperature impacts using tools such as the Assessment of Environmental and Societal Benefits of Methane Reductions Tool or the CCAC Temperature Pathway Tool. Alternatively, using the 20-year global warming potential (GWP_{20}) better captures near-term warming impact than the 100-year GWP, in addition to being more aligned with meeting the 1.5 °C target.[167] While the UNFCCC currently requires using the GWP_{100} metric when reporting aggregated emissions or removals, which systematically undervalues the climate impact of methane, reporting Parties may use other metrics in addition, such as GWP_{20} or absolute temperature potentials.[168] Indeed, using GWP_{100} alone "can lead to suboptimal policies and priorities by misleading climate actors from the top levels of governments (e.g., U.S. NDC) to grassroots organizations."[169]

AR6 has updated the metrics for methane as follows: GWP_{20} is 81.2 and GWP_{100} is 27.9.[170] **Table 2** below summarizes GWP values for methane from IPCC reports.

Table 2. GWP values for methane from IPCC reports

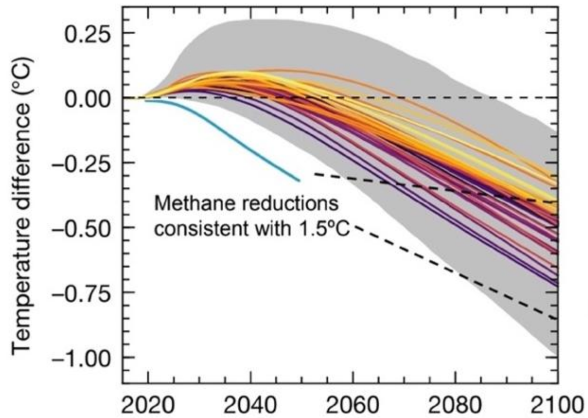
		AR6	AR5		AR4	TAR	SAR
Methane (CH_4)	**GWP_{20}**	81.2	84	86*	72	62	56
	GWP_{100}	27.9	28	34*	25	23	21
Fossil CH_4	**GWP_{20}**	82.5 ± 25.8	85		--	--	--
	GWP_{100}	29.8 ± 11	30		--	--	--
Non-fossil CH_4	**GWP_{20}**	80.8 ± 25.8	--		--	--	--
	GWP_{100}	27.2 ± 11	--		--	--	--

* with carbon cycle feedback. All methane AR6 values include carbon cycle feedback.
AR6 = 2021 Sixth Assessment Report WGI (Table 7.SM.7; Table 7.15); **AR5** = 2013 Fifth Assessment Report WGI (Table 8.A.1; Table 8.7); **AR4** = 2007 Fourth Assessment Report (Table 2.14); **TAR** = 2001 Third Assessment Report (Table 6.7); **SAR** = 1995 Second Assessment Report (Table 2.9).

Most aggregation metrics are designed for comparison with long-lived CO_2. Metrics such as CO_2-equivalence in terms of GWP and GWP* are based on mathematical relationships that are intended to make short-lived pollutants like methane comparable to the longer-term warming impact of CO_2 emissions.[171] These aggregate metrics generally ignore co-emitted pollutants with significant near-term climate impacts such as cooling aerosols. The GWP* metric seeks to account for the shorter lifetime of methane by differentiating historical emissions from changes in the rate of emissions.[172] One criticism of this approach is that it essentially "grandfathers" historical emissions, so when applied at the scale of regional or individual methane emitters, sources with high historical emissions can claim negative GWP* by reducing their rate of emissions. This is the case even if their emissions in a given year are equivalent to a new source with no historical emissions. This has led to the misuse of these metrics to claim that some sectors with large historical emissions and stable or decreasing current rates of emissions have contributed less to global warming.[173]

For these reasons, this *Background Note* follows the convention of the UNEP/CCAC *Global Methane Assessment* in using mass-based metrics, such as million metric tons of methane ($MtCH_4$), and temperature impacts rather than GWP metrics where possible.

Figure 5. Methane reductions compared to global mean surface temperature responses to changes in fossil-fuel-related emissions (CO_2 + SO_2)



Source: Shindell D. (25 May 2021) *Benefits and Costs of Methane Mitigation*, Presentation at the CCAC Working Group Meeting. *Updating* Figure 3d from Shindell D. & Smith C. J. (2019) *Climate and air-quality benefits of a realistic phase-out of fossil fuels*, NATURE 573: 408–411. *See also* United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: *BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS*.

- Under the Biden administration, the United States established significant domestic policies and international partnerships to reduce methane emissions.
    - As a Global Methane Pledge champion country,[174] the U.S. provided global leadership by helping to launch initiatives such as: the Global Methane Pledge Energy Pathway to support methane reductions in the oil and gas sector;[175] the Pledge's Food and Agriculture Pathway and Waste Pathway to advance methane mitigation in the agriculture and waste sectors,[176] including an Enteric Methane Research and Development Accelerator;[177] and the U.S. Agency for International Development (USAID) Methane Accelerator for the waste, agricultural, and energy sectors.[178]
    - At COP29 in November 2024, the second Summit on Methane and Non-CO_2 Greenhouse Gases ("COP29 Methane Summit") was convened by the United States, the People's Republic of China, and Azerbaijan.[179] The summit signaled further ambition in the sprint to cut methane and other super pollutants, as partners announced nearly $500 million in new global funding for methane abatement (bringing the total international grant funding for super pollutant mitigation to over $2 billion over the last three years), committed to new policy and regulatory steps to reduce methane emissions in the oil and gas and landfill sectors, and launched the first ever *Global Nitrous Oxide Assessment*.[180]
    - At COP28 in December 2023, the Summit on Methane and Non-CO_2 Greenhouse Gases ("COP28 Methane Summit") was convened by the United States, the People's Republic of China, and the United Arab Emirates.[181] The summit recognized the need for methane cuts to avoid overshooting 1.5 °C, called for countries' 2035 Nationally Determined Contributions (NDCs) to include non-CO_2 climate pollutants, and announced ~US$1 billion in new finance for methane reduction projects. The U.S. and China additionally agreed to renew and enhance

their bilateral cooperation on addressing the climate crisis by implementing national action plans on methane and other non-CO_2 climate pollutants.[182]

  - Domestically, the 2022 U.S. Inflation Reduction Act (IRA) allocated US$369 billion for climate and clean energy policies, including ~US$20 billion in incentives to reduce greenhouse gas emissions, including methane from the agriculture sector,[183] along with US$1.55 billion for reducing oil and gas sector emissions through the Methane Emissions Reduction Program[184] and a fee on methane leaks.[185] The IRA is estimated to reduce U.S. GHG emissions by 40% below 2005 levels by 2030.[186]

- Recent policy shifts in the U.S. threaten this policy and partnership foundation for cutting global methane emissions. The shifts include the reversal of the U.S. methane fee.[187] Now is the time for all stakeholders, including those in the U.S., to underscore that avoiding methane waste is an opportunity to protect domestic energy security, bolster economic growth, and increase competitiveness of energy supply chains.[188]

IGSD's (2024) *Primer on Cutting Methane: The Best Strategy for Slowing Warming in the Decade to 2030* provides further information on the science of methane mitigation and why action is urgently needed; current and emerging mitigation opportunities by sector; national, regional, and international efforts that can inform emergency global action on methane; and financing initiatives to secure support for fast methane reduction.

B. Tropospheric ozone (O_3)

Tropospheric ozone is a local air pollutant and significant greenhouse gas that has added 0.1–0.4 °C of warming since the pre-industrial period.[189] Ozone is not directly emitted but is a product of atmospheric reactions with precursor pollutants, which include methane (itself an SLCP), volatile organic compounds, carbon monoxide, and nitrogen oxides (NO_x). In addition to contributing to warming, it is responsible for millions of premature deaths,[190] billions of dollars' worth of crop losses annually,[191] and weakening of carbon sinks.[192]

Mitigation

- Methane contributes 35% to today's tropospheric ozone burden, and reducing it reduces tropospheric ozone levels[193] and improves air quality.[194] Methane is likely to play a greater role in tropospheric ozone formation as ozone's other precursors are reduced by air pollution controls.[195]
- Methane is the last remaining major ozone precursor not explicitly controlled under the 1999 Gothenburg Protocol to Abate Acidification, Eutrophication, and Ground-Level Ozone to the UNECE Convention on Long-Range Transboundary Air Pollution.[196]
- Local air quality impacts from surface ozone (particularly in cities) tend to depend on emissions of NO_x and non-methane volatile organic compounds (NMVOCs), as well as weather and seasonal patterns. Ozone's global climate impacts are controlled by its background level in the atmosphere, which depends on methane as well as NO_x levels.[197] Policy changes and mitigation also need to consider reducing NO_x and NMVOCs together, as complex interactions of these precursors can lead to increases in urban ozone levels if they aren't reduced in equal measure.[198]
- Connecting ozone mitigation to both health and climate change offers an opportunity to enhance co-benefits of precursor reduction.[199]

C. Black carbon

Like tropospheric ozone, black carbon is a local air pollutant and is often addressed under national or regional air pollution laws, as well as through the voluntary programs of the CCAC.[200] Black carbon is not a well-mixed greenhouse gas, but a powerful climate-warming aerosol that is a component of fine particulate matter (specifically $PM_{2.5}$) that enters the atmosphere through the incomplete combustion of fossil fuels, including biofuels and biomass.[201]

Fossil fuel combustion is the largest source of air pollution particles and tropospheric ozone, which kills 810 million[202] people every year. Black carbon alone is directly associated with upwards of 150,000 excess deaths per year globally.[203] Cutting black carbon and tropospheric ozone can save up to 2.4 million lives every year and prevent the loss of crops by more than 50 million tons, worth US$4 billion to US$33 billion a year, as calculated in 2011,[204] while also preventing "disproportionate" impacts on regional feedback loops and tipping systems (such as ice sheets) that are sensitive to ice-albedo feedbacks.[205]

Mitigation

- According to the CCAC and the 2011 UNEP/WMO Integrated Assessment of Black Carbon and Tropospheric Ozone, 80% of global black carbon emissions can be reduced with existing measures.[206] The following measures should be implemented:
    - Ensuring fast ratification of the Gothenburg Protocol and the 2012 amendment, which includes controls for black carbon, by countries who have not already done so;[207]
    - Reducing on-road and off-road diesel emissions by mandating diesel particulate filters while eliminating diesel and other high-emitting vehicles and shifting to cleaner forms of transportation;[208]
    - Eliminating flaring, while shifting to clean energy;[209]
    - Switching to clean cooking and heating methods;[210] and
    - Banning heavy fuel oil in the Arctic and establishing black carbon emission standards for vessels by amending Annex VI of the International Convention for the Prevention of Pollution from Ships (MARPOL).[211]
- Arctic Council countries are collectively on track to meet their goal of reducing black carbon by 25–33% below 2013 levels by 2025, despite lagging progress from Russia.[212] Technologies already exist that, with more ambitious policy, could quickly cut black carbon emissions by 50%.[213]
- The Clean Air Fund, in its 2023 report on *The Case for Action on Black Carbon*, recommended the following actions be taken by national policy makers and regulators:[214]
    - Include black carbon in NDCs for the 2025 global stocktake in a way that provides additive emissions reduction, beyond what would be achieved with decarbonization and methane mitigation alone, and include short-lived climate forcers in national inventories when reporting to the UNFCCC;
    - Prioritize decarbonization of brick kilns, diesel engines, and kerosene lamps;
    - Promote the use of black carbon-free sources of residential biofuels; and,
    - Support subnational regions, including cities, in their efforts to cut black carbon.
    - In addition, the Arctic Council and its observer countries are recommended to ramp up their efforts and ambition, pursuing aggressive black carbon reductions post-2025.

- The report also calls on countries that are funding decarbonization efforts under Article 6.2 of the Paris Agreement to prioritize "projects that simultaneously have the greatest potential to reduce black carbon emissions," and for multilateral development banks and philanthropies to build up financing capacity for black carbon mitigation programs.

D. Hydrofluorocarbons (HFCs)

Hydrofluorocarbons (HFCs) are factory-made chemicals primarily produced for use in refrigeration, air conditioning, insulating foams, and aerosol propellants, with minor uses as solvents and for fire protection.

Mitigation

- The Montreal Protocol on Substances that Deplete the Ozone Layer (Montreal Protocol) is successfully phasing out the production and use of ozone-depleting and potent climate pollutants, including chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), preventing GHG emissions that otherwise could have equaled or exceeded the emissions of CO_2 in 2010.[215] As of 2021, effective radiative forcing from HCFCs is declining, five years earlier than expected.[216]
  - Avoided warming from the Montreal Protocol is delaying the first appearance of ice-free Arctic summer by up to 15 years.[217]
  - By phasing out ozone depleting substances that are also super climate pollutants, the Montreal Protocol has avoided 0.1–0.2 °C to date of global average surface warming and 0.2–0.6 °C in the Arctic. This increases to 0.5–1.0 °C of global surface warming avoided by mid-century.[218]
  - By the end of the century, the Montreal Protocol's steady progress over its 35 years of operation will avoid up to 2.5 °C of warming that otherwise would have already pushed the planet past irreversible tipping points.[219] About 1.7 °C of this avoided warming comes from the Protocol's mandatory reduction of super polluting chemicals—CFCs, HCFCs, and now HFCs—used primarily as refrigerants in cooling equipment. An additional 0.85 °C of warming will be avoided by protecting our planet's forests and other carbon sinks from damaging ultraviolet radiation that reduce their ability to pull CO_2 out of the atmosphere and store it safely in terrestrial sinks.[220]
  - This planet-saving climate benefit is in addition to achieving its original objective of putting the stratospheric ozone layer on the road to full recovery by 2066.[221]
  - Emissions of these ozone depleting super-climate pollutants between 1955 and 2005, were 20% more effective at warming than CO_2,[222] accounted for 37% of anthropogenic Arctic warming, and one-third of the loss in September sea ice extent due to anthropogenic emissions.[223]
  - Narrowing exemptions for CFCs and HCFCs used as feedstocks (in plastics, for example) and produced as by-products could further ensure these benefits.[224] Atmospheric measurements reveal increasing concentrations of five CFCs banned under the Montreal Protocol but likely emitted as by-products and not subject to current controls.[225]
- HFCs are now being phased down under the Montreal Protocol's Kigali Amendment, with the potential to avoid up to 0.5 °C of warming by 2100.[226]

- The initial phasedown schedule of the Kigali Amendment would lock in reductions limiting warming from HFCs in 2100 to about 0.04 °C, avoiding nearly 90% of the potential, or up to 0.44 °C.[227] Efficient implementation of the Kigali Amendment could avoid nearly 0.1°C of warming by 2050.[228]
- Accelerating the phasedown could reduce HFC emissions by an additional 72% in 2050, increasing the chances of staying below 1.5 °C this century.[229]
- In addition to a faster phasedown schedule, more mitigation is available from recycling and destroying HFC "banks" embedded in products and equipment; early replacement of older inefficient cooling equipment using the old HFC refrigerants; and reducing refrigerant leaks through better design, manufacturing, and servicing.[230]
- Globally, adopting lifecycle refrigerant management practices, including reducing leaks and stopping end-of-life venting of HFCs from refrigerators and air conditioners, could avoid up to 91 $GtCO_2e$ of emissions by the end of the century.[231]
- The Kigali Amendment also requires Parties to destroy HFC-23, a by-product of the production of HCFC-22, to the extent practicable, which will provide additional mitigation not included in the 0.5 °C calculation.[232] Abatement measures already exist to substantially reduce HFC-23 emissions,[233] although mismatches between reported and observed HFC-23 emissions indicates that abatement in some countries needs to be increased.[234]
- Improving energy efficiency of cooling equipment during the HFC phasedown can more than double the climate benefits in CO_2e by reducing emissions from the fossil fuel power plants that are still providing the electricity to run the equipment.[235]
- As of April 2025, 162 countries and the European Union have accepted, ratified, or approved the Kigali Amendment, including China and India.[236]
- Cooling demand is predicted to triple by 2050, due to rising global temperatures, incomes, and populations.[237] Solutions exist and must be leveraged to meet this demand sustainably[238] and equitably,[239] while cutting SLCPs.[240] The Global Cooling Pledge, launched at COP28, was endorsed by more than 60 countries who committed to actions that would avoid 78 billion tons of CO_2e by 2050, including: ratifying the Kigali Amendment; using the Montreal Protocol Multilateral Fund to act more quickly on the phaseout of HCFCs and the phasedown of HFCs; establishing Minimum Energy Performance Standards (MEPS); creating or revising guidance on the use of low-GWP and high efficiency cooling technology; addressing HFC banks and lifecycle management; and introducing passive cooling strategies into national building codes.[241]

- On 21 September 2022, the U.S. Senate approved ratification of the Kigali Amendment.[242]
  - The U.S. is implementing the Kigali phasedown schedule through the 2020 American Innovation and Manufacturing (AIM) Act. The AIM Act and related implementing regulations will reduce the production and consumption of HFCs by 85% by 2036.[243] Twelve U.S. states have instituted HFC prohibitions for products and equipment where low-GWP alternatives are available, and six more have proposed HFC bans.[244]
  - By implementing the Significant New Alternatives Policy (SNAP) and Refrigerant Management Programs (RMP) along with the AIM Act, HFCs emissions can be reduced by at least 54% below 2020 levels by 2035. There is also significant potential for additional reductions from end-of-life disposal, as these are not captured by current modeling.[245]

E. Nitrous oxide (N_2O)

While not short-lived and thus not an SLCP, N_2O is a potent greenhouse gas with a global warming potential that is 273 times greater than CO_2,[246] contributing the equivalent of about 10% of today's CO_2 warming.[247] N_2O also is the most significant anthropogenic ozone-depleting substance (ODS) not yet controlled by the Montreal Protocol.[248]

N_2O emissions have accelerated over the last 20 years.[249] The levels of N_2O in the atmosphere, already 25% higher than pre-industrial levels,[250] now exceed the highest model projections.[251] Anthropogenic N_2O emissions in 2020 were more than 20% of the ozone-depleting potential of peak CFC emissions in 1987.[252]

Sources

- Since 1980, anthropogenic N_2O emissions have increased by 40%,[253] with no sign of slowing.[254]
  - Agricultural emissions make up the majority (75%) of human-driven emissions of N_2O, with a smaller part (5%) coming from industrial processes. The remaining emissions come from fossil fuel combustion, wastewater treatment, aquaculture, and biomass burning.[255]
  - The agriculture, forestry, and land use sector (AFOLU) accounts for ~80% of global anthropogenic N_2O emissions,[256] contributing approximately 1.8 $GtCO_2e$/yr (6.6 Mt N_2O/yr) between 2010 and 2019.[257] In 2020, agricultural N_2O emissions from direct and indirect sources accounted for ~2.2 $GtCO_2e$ (8 Mt N_2O).[258]
  - China drove 40% of the worldwide increase in N_2O emissions rate between 1980–2020, with nearly half of its emissions in the 2010s attributable to agriculture.[259]
  - Under current policies, agricultural N_2O emissions are projected to rise by 8% from 2021–2030.[260]

Global Nitrous Oxide Assessment

- Launched at COP29,[261] the 2024 *Global Nitrous Oxide Assessment* projects that N_2O emissions will continue to increase and that, without ambitious mitigation,[262] there is no plausible pathway to keep the 1.5 °C Paris guardrail within reach while providing for sustainable development.[263]
- Technically feasible abatement, accompanied by food system transformation, could reduce anthropogenic N_2O emissions by 40% by 2050 and by nearly 60% by 2100.[264] This would avoid emissions equivalent to 235 million tons of CO_2 or 6 years' worth of fossil fuel emissions at the current rate.[265]
  - Mitigation measures to achieve these deep N_2O reductions would simultaneously lower livestock methane emissions. The combined N_2O and methane reductions would lead to 0.1 °C of cooling by 2100, relative to a world where N_2O emissions keep growing at their current rate.[266]
- Reducing N_2O emissions to levels compliant with the 1.5 °C Paris Agreement guardrail will protect stratospheric ozone. Ambitious mitigation could provide five times the ozone benefits as the phaseout of HCFCs by 2100.[267]
  - Ozone levels will reach an all-time low if N_2O emissions continue their unabated increase, leading to harmful UV levels.[268]

- Industrial emissions are the "low-hanging fruit" of N_2O mitigation.[269] Most industrial emissions are produced in the manufacture of nitric and adipic acids, and they can be reduced quickly by established technologies to deliver climate and ozone benefits.[270]
  - In the industrial sector, abatement technology has been available and utilized by manufacturers in developed countries since the 1990s.[271] Proven abatement technology at nitric and adipic acid production facilities could reduce 86% of projected industrial N_2O emissions by 2030.[272]
  - Estimates of the number of operational adipic acid plants range from 21 to 39.[273] China hosts 11 plants[274] while the U.S. hosts two.[275] Of these, one plant in the U.S. and all of China's plants are assumed to operate without (or with significantly less) pollution control technology than the industry standard.[276]
  - Currently, the U.S. and China contribute nearly 80% of all industrial N_2O emissions.[277] China and the U.S. are projected to remain the major two emitters of industrial N_2O in 2030, contributing over 75% of the total.[278]
  - In November 2023, the U.S. and China agreed to cooperate on managing N_2O emissions,[279] focusing on the industrial sector.[280] A White House summit on industrial N_2O in July 2024 showcased the plans by U.S. manufacturers to abate 50% of their N_2O pollution by 2025,[281] highlighting potential paths forward for China.
- In the agriculture sector, solutions exist to mitigate N_2O emissions while still producing enough food to meet the demands of a growing human population.[282] However, achieving the full climate and ozone benefits of N_2O mitigation requires deeper changes to the global food system, including a shift to more plant-based diets in some regions.[283]
  - Technical measures include precision farming using slow-release fertilizers and nitrogen inhibitors, which suppress the microbial activity that produces N_2O.[284]
  - A study has found that variable rate technology can increase yields by 1–10% while reducing 4–37% of nitrogen fertilization.[285]
  - Adapting solutions for smallholder farmers in the Global South requires additional attention.[286]
  - Another potential solution, the SOP LAGOON product line,[287] stimulates nitrogen uptake in crops and inhibits GHG emissions from manure, according to peer-reviewed field experiments with the product.[288]
- Reducing N_2O benefits the health of humans and ecosystems.
  - Mitigating N_2O from fossil fuels and agriculture also reduces co-emitted pollutants from shared sources. These include harmful air pollutants such as NO_x, which contributes to the formation of tropospheric ozone (**Section 3B**), as well as particulate matter pollution from emissions of ammonia.[289] Ambitious abatement of these sources would improve air quality and avoid 20 million premature deaths by 2050.[290]
  - Protecting stratospheric ozone, by mitigating N_2O and other ODS (**Section 3D**), reduces damaging UV radiation that causes skin cancers and cataracts.[291] UV damage from unabated N_2O would also reduce plant productivity and damage the carbon sink.[292]
  - Sustainably managing agricultural inputs of N_2O and other forms of nitrogen can help alleviate water pollution and eutrophication from agricultural runoff, while easing pressure on the disrupted global nitrogen cycle.[293]

- Similar to the unmasking of sulfate aerosols that results from fossil fuel decarbonization (**Section 2**), improved nitrogen management in the agricultural sector would reduce nitrate and secondary aerosols that have a cooling effect, which masks warming in the near-term.[294] However, N_2O mitigation still delivers long-term climate, ozone, and health benefits.[295]
- N_2O mitigation strategies need to account for potential trade-offs that might lead to unintended increases of methane or CO_2 emissions.[296]
    - Some manure and soil management strategies that aim to decrease emissions of specific GHGs could inadvertently increase others.[297] Ammonia-based fuels for decarbonization could also offset CO_2 cuts by enhancing N_2O emissions.[298]

4. Other fast mitigation strategies can complement efforts to slow warming in the near term

A. Protecting Arctic albedo and permafrost

Rapid reductions in super climate pollutants are key to protecting the Arctic. The *Global Methane Assessment* calculated that strategies to cut methane emissions by 40–45% by 2030 (relative to projected baseline emissions in 2030) could avoid nearly 0.3 °C globally by the 2040s, and 0.5 °C in the Arctic by 2050, 60% more than the global average.[299] The 2011 UNEP/WMO Integrated Assessment of Black Carbon and Tropospheric Ozone calculated that fully implementing measures targeting methane and black carbon could reduce the rate of global warming by half and reduce Arctic warming by two-thirds.[300]

- The Arctic is nearly five times more sensitive to black carbon emitted in the Arctic region than from similar emissions in the mid-latitudes.[301] In the Arctic, black carbon not only warms the atmosphere but also facilitates additional warming by darkening the snow and ice and reducing albedo, or reflectivity, allowing the darker surface to absorb extra solar radiation and cause further melting.[302]
    - Heavy-Fuel Oil (HFO) used in shipping is a significant source of black carbon and sulfates.[303] The International Maritime Organization (IMO) ban on HFO use in the Arctic came into effect in July 2024 for some ships, with waivers and exemptions for others until July 2029.[304] (HFO has been banned in the Antarctic since 2011.[305])
    - Because of the exemptions, the HFO ban will not have a big impact this decade. If the measures that will go into effect in July 2024 had been in effect in 2019, they would have banned only 16% of HFO used in the Arctic and reduced only 5% of the black carbon.[306] However, if the Arctic HFO ban were imposed without the waivers or exemptions, black carbon emissions could have been reduced by 30%.[307]
    - In 2019, Arctic Council countries set a collective voluntary target of reducing black carbon emissions by 25–33% by 2025 compared to 2013 levels.[308] Adopting best available techniques could halve black carbon emissions by 2025 and surpass the current goal.[309] These reductions would improve air quality by reducing exposure of fine particle concentrations from 18 million to 1 million people by 2050 and avoid 40% of air pollution-related deaths in Arctic Council countries by mid-century.[310]
    - In 2021, the IMO adopted a voluntary resolution to reduce black carbon emissions in the Arctic after the annual meeting of the IMO's Marine Environment Protection Committee. In addition to this resolution, the Committee also agreed to revise their

GHG Strategy, adopt a voluntary resolution on using cleaner fuel in the Arctic, and address marine plastic litter from ships.[311]

    - Banning investments in oil and gas development in the Arctic can help to further protect the region. All the major U.S. banks—Bank of America, Goldman Sachs, JP Morgan Chase, Wells Fargo, Citi, and Morgan Stanley—have committed not to fund oil and gas exploration in the Arctic,[312] although some banks have rolled back these commitments.[313] Insurance companies are also starting to commit to banning coverage of Arctic oil projects, including AXA, Swiss RE, and Zurich Insurance.[314]
- Additional strategies being investigated for protecting and restoring Arctic ice include enhancing albedo of Arctic sea ice and thickening sea ice.[315]
    - Ocean Visions has developed an interactive roadmap on Arctic sea ice preservation strategies, which summarizes potential pathways towards implementation at the regional and global scale along with impacts, costs, and governance implications. It also identifies priorities for additional research and investment.[316]

B. Protecting forests and other carbon sinks

About half of the anthropogenic CO_2 emitted each year is removed by the ocean and land sinks over the span of 30 years.[317] These sinks are slowing their carbon uptake, and some are approaching vulnerable tipping points. Carbon budget estimates do not account for catastrophic carbon sink loss, and thus the committed warming following net zero will depend on the state of these carbon sinks.[318]

i. Land sinks at risk of tipping

Deforestation combined with global warming risks enhancing warming feedbacks and crossing ecosystem tipping points, including loss of the Amazon and boreal forest.[319] Halting the destruction of forests and other carbon sinks so they continue to store carbon and do not turn into sources of CO_2 can provide fast mitigation, while also protecting biodiversity.[320] This also requires stopping forest bioenergy, which is not a climate solution.[321]

- Under current warming trends, the global land sink, which now mitigates ~30% of carbon emissions and has avoided 0.4 °C since 1900,[322] could be cut by half as early as 2040, as increasing temperatures reduce photosynthesis and speed up respiration,[323] calling into question national pledges under the Paris Agreement that rely on land uptake of carbon to meet mitigation goals.[324] Loss of forests and other sinks contributes to warming through loss of carbon sinks and increased carbon dioxide and other GHG emissions (biogeochemical effect) through changes in the local surface energy budget (biophysical effect).
    - Tropical and boreal forest dieback could contribute up to 200 PgC [733 $GtCO_2$] by 2100.[325] If all the carbon stored in the Amazon were released (10 years' worth of human emissions), the planet could warm by 0.3 °C.[326] The boreal forest carbon sink rivals the Amazon's, representing 30% of global forest area, and close to half of the global terrestrial carbon sink.[327]
    - Degradation of tropical moist forests contributes warming that may push these forests towards their tipping points. Patches of degraded tropical moist forests are on average 0.78 °C warmer than intact forests. CO_2 emissions from tropical forest degradation also contribute an average 0.026 °C across all tropical land areas

(biogeochemical effect), which is comparable to the biophysical warming of 0.022 °C. The warming impacts from forest degradation could be extensive, as nearly a quarter (24%) of the world's tropical moist forests are degraded according to 2010 satellite images.[328] A ~4 °C increase in air temperatures could induce a tipping point that threatens the canopy of tropical forests by pushing vegetation past their upper temperature limit for photosynthesis.[329]

  - Forest fires damage carbon sinks and deplete the remaining carbon budget. Since 2001, carbon loss from forest fires has increased 60%.[330] This was driven by emissions from boreal and temperate forest fires, even as fire emissions from tropical forests slightly declined.[331]
  - Accelerated warming in the boreal zones has intensified wildfires[332] and pest-outbreaks,[333] leading to large-scale tree mortality. Such events have been both abrupt and irreversible, as intermediate stages of boreal forest regeneration are proving unstable.[334] More frequent and severe fires increase the risk of boreal forests switching from a carbon sink to a carbon source,[335] and this switch has already occurred in North America due to boreal wildfires between 1985–2016.[336]
  - The increased incidence of boreal wildfires has been linked to drier air, or vapor pressure deficit (VPD), that draws moisture out of the soil and vegetation.[337] Soil desiccation is a self-amplifying feedback contributing additional warming,[338] which is projected to accelerate by mid-century under a high emissions scenario (SSP5-8.5), although it is significantly reduced under a low emissions scenario (SSP1-2.6).[339] If warming continues along a high-emissions trajectory, this feedback will amplify as early as mid-century and lead to an increase fires across North America and Europe.[340] Nearly half of the increase in VPD is attributable to emissions from the world's top 88 carbon-emitting corporations.[341]
  - Warming is also shifting the range of boreal forests further north into bare snow-covered tundra, reducing albedo and creating warmer winters in the region.[342] While boreal forest range shifts have high potential to propel self-amplifying feedbacks, the net warming impact remains uncertain.[343]
- The Amazon forest is already within the bounds of its estimated tipping point, 20-40% of complete loss,[344] with 20% destroyed completely and an additional 6% beyond repair absent human intervention.[345]
  - In comparison to other parts of the Earth system, like ice sheets, parts of the biosphere like the Amazon can tip and collapse quickly, on the scale of months to decades.[346]
  - Continued deforestation and drying in the Amazon under high-emissions scenarios could result in up to a 50% loss in forest cover by 2050.[347]
  - Changes to the global water cycle may be pushing the Amazon to a tipping point.[348] In the northern Amazon region, fire weather conditions (hot, dry, and flammable) now prevail up to 120 days a year, three times more days than experienced at the end of the 20th century.[349] The combination of drier conditions, deforestation, and warming have been reducing Amazon forest resilience since 2000, increasing the risk of dieback.[350]
  - With increased deforestation, including from fires, greater disturbances, and higher temperatures, there is a point beyond which the Amazon rainforest would be difficult to reestablish,[351] with recent measurements suggesting that the

southeastern area of the Amazon has already shifted to a net carbon source as tree mortality increases and photosynthesis decreases.[352]
    - In 2023, the Amazon River Basin (83% of which is rainforest) entered what has been called "the most extreme" drought in the historical record, marked by 120-year low water levels in many of the river's tributaries.[353] Droughts strain the forest's resilience and could trigger a tipping point.[354]
- Conservation International estimates that Earth's ecosystems contain 139 billion metric tons (Gt C) [510 $GtCO_2$] of "irrecoverable carbon," defined as carbon stored in natural systems that "are vulnerable to release from human activity and, if lost, could not be restored by 2050." The highest concentrations of irrecoverable carbon are in the Amazon (31.5 Gt C) [115.5 $GtCO_2$], the Congo Basin (8.1 Gt C) [29.7 $GtCO_2$], and New Guinea (7.3 Gt C) [26.8 $GtCO_2$], with additional reserves in boreal forests, mangroves, and peatlands.[355]
- Recent research has indicated that, while the largest and dominant methane sink is the atmosphere, trees in temperate and tropical forests store a small but significant amount of methane.[356] Restoration of these forests could therefore provide an additional climate benefit.[357]

Nature-based solutions help limit warming in three ways: first, protecting forests and sinks prevents the release of carbon; second, restoring critical forests and sinks sequester carbon; and third, improving land management can both reduce emissions of carbon, methane, and N_2O and sequester carbon.[358]

- Effective ways to protect forests, peatlands, and other sinks include:
    - Promoting forest protection and pro-forestation to allow existing forests to achieve their full ecological potential;[359]
    - Preserving existing peatlands and restoring degraded peatlands;[360]
    - Restoring coastal "blue carbon" ecosystems;[361] and
    - Prohibiting bioenergy.[362]
- Global government-led efforts to protect forests are increasing, but still insufficient.
    - At COP26, world leaders agreed to halt deforestation by 2030 in the Glasgow Leaders' Declaration on Forests and Land Use. 145 countries committed to the agreement, including Brazil, China, Russia, and the United States, covering about 91% of the world's forests.[363] The COP28 Global Stocktake Outcome formally recognized the need to reduce deforestation by 2030 in line with Paris commitments.[364]
    - Brazil, which will host COP30, has promised to deliver a "tropical forests COP" and, at COP28, proposed launching a Tropical Forests Forever fund to raise US$250 billion for forest conservation.[365]
    - However, since COP26, global deforestation has increased, and policies and finance are not yet aligned with the Declaration's stated goals.[366] In addition, countries' pledges to protect forests in NDCs and through initiatives such as the Bonn Challenge frequently lack clarity. This leads to overlapping and competing claims about what land is being used for what purpose,[367] as well as uncertainties about how these commitments will impact agriculture and people.[368] Forest protection and restoration on their own are not sufficient to solve the climate crisis. They must be coupled with emissions cuts.[369]

ii. The ocean carbon sink is weakening

The ocean carbon sink, which has absorbed roughly 30% of anthropogenic CO_2 emissions since the Industrial Revolution,[370] may be losing its ability to mitigate ever-increasing human emissions. Carbon uptake has slowed by 15% between 1994–2014.[371] Half of this recent slow-down is from anticipated declines in the ocean's capacity to absorb CO_2 due to rising atmospheric CO_2 and warmer ocean temperatures. The rest of this recent slow-down is attributable to warming-induced declines in ocean mixing, especially weakening of the AMOC, which normally transports CO_2-rich waters to the deep ocean.[372] If slowing ocean uptake continues, more aggressive emissions reductions will be required to meet net zero targets, as they assume a static ocean carbon sink.[373]

C. Removing super pollutants from the atmosphere: eliminating short-lived pollutants for long-term benefits

Even though methane is short-lived in the atmosphere, with over 90% naturally oxidized (converted) to CO_2 after 40 years, there are significant benefits to removing methane before it can realize its full impact on the climate system. Short-lived does not mean short-term impacts. Temperature anomalies from methane emissions can persist for centuries. This is due to carbon-climate feedbacks and lagging responses from other parts of the climate system, such as the slow release of heat from oceans.[374]

As described in **Section 3A**, atmospheric methane concentrations are rapidly approaching 2 parts per million (2 ppm or 2,000 ppb), an increase of over two and a half times pre-industrial levels.[375] Both increasing anthropogenic emissions and growing natural emissions, in particular from tropical wetlands, appear to be driving the surge observed over the past four years.[376]

Despite its large impact on warming, methane in the air is present in very low concentrations, making up less than 0.01% of the atmosphere. As there is no commercial technology currently available to remove methane at concentrations below ~1,000 ppm,[377] and methane emissions typically occur at levels closer to 2 ppm,[378] a technology gap exists for methane removal. This technology gap, combined with the prospect of increasing natural methane emissions in a warmer and wetter world—as well as the potential for a "methane emissions gap" between reductions needed to meet climate goals and the technologies available to achieve them—have led researchers to begin exploring the concept of atmospheric methane removal.[379] The short lifetime of methane in the atmosphere also offers the tantalizing potential to restore methane concentrations to pre-industrial levels and shave off the 0.5 °C of warming due to anthropogenic methane emissions, if a method to remove methane from the atmosphere could be developed.[380]

The U.S. National Academies of Sciences, Engineering, and Medicine (NASEM) published a consensus study report, *A Research Agenda Toward Atmospheric Methane Removal*, in October 2024. The report describes priority research that should be addressed within the next 3–5 years to lay the groundwork for a second-phase study that will address "technical, economic, and social viability of technologies to remove atmospheric methane at climate-relevant scales."[381] In theory, removing the equivalent of three years' worth of current anthropogenic methane emissions (and continuing to remove about 10% of current annual emissions) would reduce warming by 0.21 °C; further, removing one year's worth of methane emissions would reduce transient warming almost four times more than removing one year's worth of CO_2 emissions (0.07 °C for methane compared to 0.02 °C for CO_2).[382] However, these estimates should be considered preliminary, given the early stage of research on all forms of atmospheric methane removal, and that there are no known technologies currently available capable of oxidizing methane at 2 ppm.[383]

It is important to distinguish between oxidation of higher concentrations of methane in coal mines or dairy barns (methane not in the "free atmosphere") and atmospheric methane removal, defined by the NASEM Committee as "human interventions to accelerate the conversion of methane in the atmosphere to a less radiatively potent form or to physically remove methane from the atmosphere and store it elsewhere. The term "atmospheric methane removal" is also used when human interventions increase the sink and decrease the net flux from ecosystems to the atmosphere, or make this flux negative."[384] Some technologies are being developed to work at concentrations around 1,000 ppm and will contribute to expanding the range of mitigation options for these sources.[385]

The NASEM report provided a preliminary assessment of five potential atmospheric methane removal approaches:

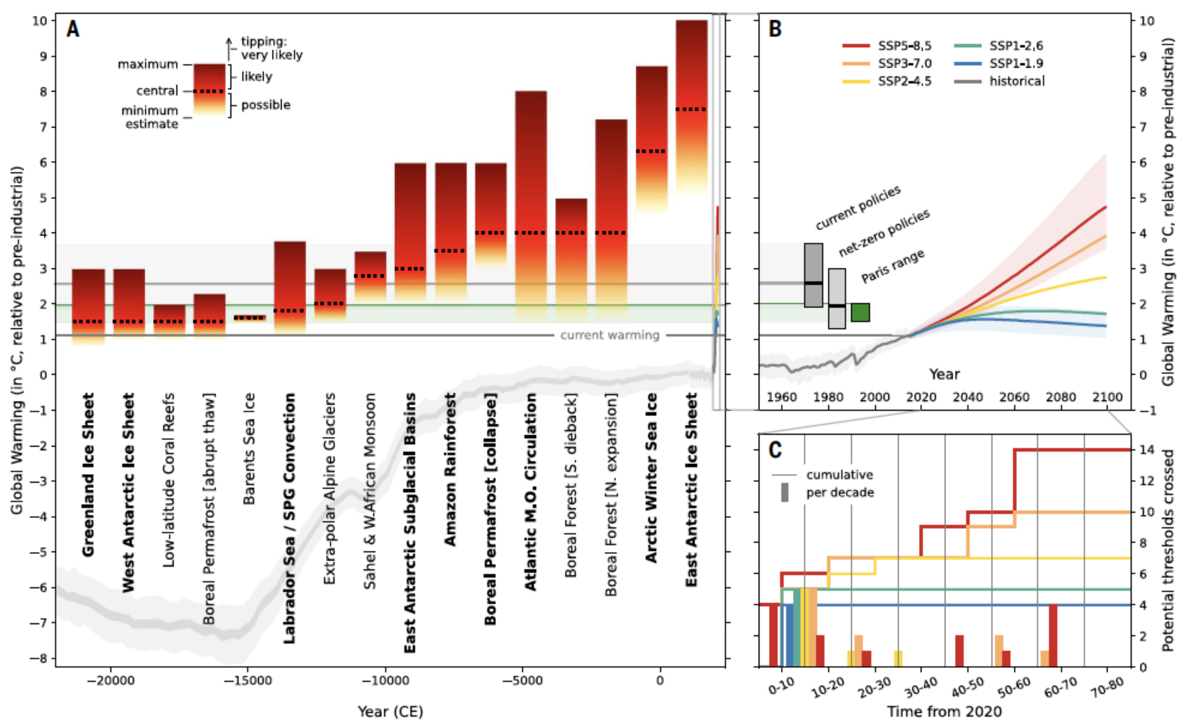
- **"Methane reactors** — physically bounded systems that use active air flow to capture or convert methane to a different chemical species with lower warming potential. The largest barriers to making reactors climate beneficial or cost effective are the need to heat a lot of air above ambient temperatures and the energy required for moving air and operating the reactors.
- **Methane concentrators** — materials or devices that can separate or enrich methane relative to other atmospheric components. While the physical and chemical properties of methane make separation extremely challenging, if a technology could efficiently concentrate methane from low to modestly elevated concentrations, it could enable methane reactor technologies.
- **Surface treatments** — applying a catalyst to a surface to convert methane to a different species with lower atmospheric warming potential when air passes over the surface. Effective treatments would have contact with a high volume of air, but they would be limited by the size of the surface and the durability of coatings.
- **Ecosystem uptake enhancement** — amendments or practices to augment the net uptake of methane, by or within primarily ecosystems that are already managed by humans, such as agricultural soils or plantations. Ecosystem amendments would likely need to be reapplied and hold the potential for ecosystem co-benefits, but unintended consequences for nutrient cycling, biodiversity, and ecosystem services are not well understood.
- **Atmospheric oxidation enhancement** — accelerated conversion of methane in the free atmosphere by augmenting the abundance or lifetime of reactive species. Continuous application of large quantities of materials would be required, potentially making this approach resource-intensive, but it does not have the same energy and heating requirements as other atmospheric methane removal technologies. The potential unintended consequences of this technology are substantial and not well understood."[386]

The NASEM report recommended a research agenda with five research areas and funding of US$50–80 million per year over 3–5 years to inform a second-phase assessment.[387] The Committee highlighted the importance of integration across disciplinary fields and the value of early public engagement.[388] None of the research questions identified in the report would require technology deployment. Importantly, the report concludes that atmospheric methane removal technologies, even if successfully developed, will not replace mitigation on timescales relevant to limiting peak warming this century.[389]

5. Feedbacks and tipping points are key to understanding the planetary emergency and the need for speed

The "evidence from tipping points alone suggests that we are in a state of planetary emergency: both the risk and urgency of the situation are acute," according to Tim Lenton and colleagues,[390] underscoring the need for speed in deploying fast mitigation strategies to limit near-term warming while simultaneously pursuing long-term decarbonization to keep sight of the 1.5 °C guardrail. The IPCC defines tipping points as "critical thresholds in a system that, when exceeded, can lead to a significant change in the state of the system, often with an understanding that the change is irreversible. An understanding of the sensitivities of tipping points in the physical climate system, as well as in ecosystems and human systems, is essential for understanding the risks associated with different degrees of global warming."[391] Earth system models project a cluster of six such abrupt shifts (not necessarily irreversible) between 1 °C and 1.5 °C of warming and another eleven between 1.5 °C and 2 °C,[392] as confirmed by two IPCC Special Reports.[393] A recent assessment finds that exceeding 1.5 °C increases the likelihood of triggering or committing to six self-propagating climate tipping points (**Figure 6**).[394] Another new modelling approach demonstrated a non-linear acceleration of tipping risks above 2 °C, driven by ice sheet changes and tipping of ocean circulation in the Atlantic.[395]

Figure 6. Abrupt climate changes as global temperatures increase



Source: Armstrong McKay D. I., Staal A., Abrams J. F., Winkelmann R., Sakschewski B., Loriani S., Fetzer I., Cornell S. E., Rockström J., & Lenton T. M. (2022) *Exceeding 1.5 °C global warming could trigger multiple climate tipping points*, SCIENCE 377(6611): eabn7950, 1–10, Figure 2.

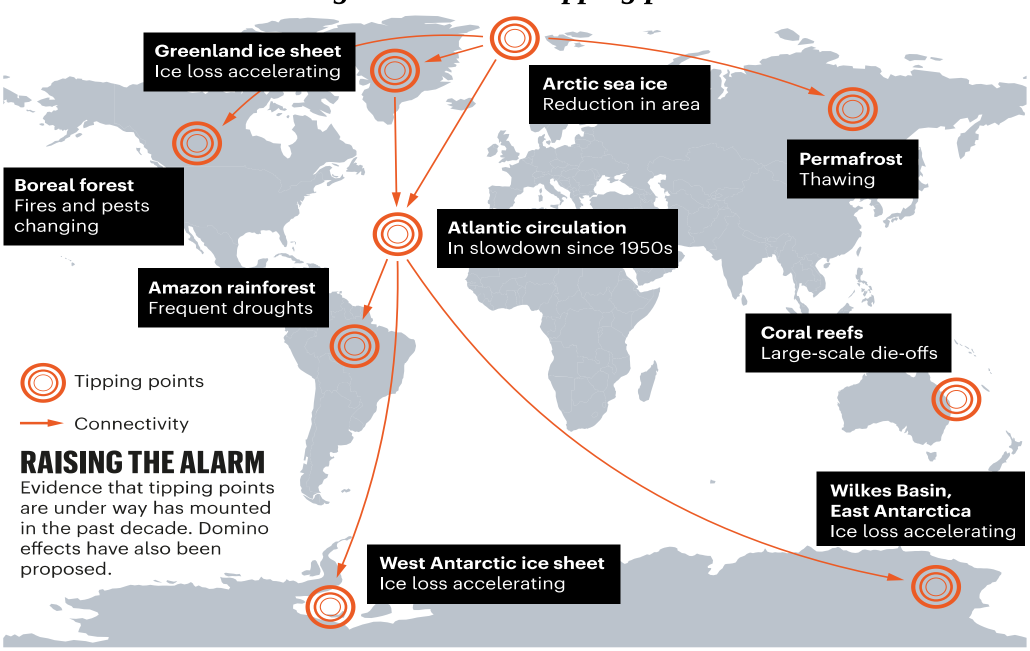
A. Climate models ignore or underestimate key feedback and tipping point risks

Climate models either ignore or underestimate key feedbacks and tipping point risks.[396] Domino-like interactions among these systems are projected to lower thresholds and increase the risk of triggering a global cascade of tipping points (**Figure 7**).[397] Nor do climate models account for other circumstances that have been shown to lower tipping thresholds, including increasing rates of warming,[398] pressure from multiple stressors, or increased variability in a single stressor.[399] Climate models that exclude planetary feedbacks such as permafrost thaw and wetland methane emissions underestimate future warming.[400] These exclusions and limitations mean that models may miss additional as-yet-undiscovered tipping points.[401]

Self-amplifying feedbacks, including the loss of Arctic sea ice, are among the most vulnerable links in the chain of climate protection.[402] Climate-driven changes in clouds act as another self-amplifying feedback leading to more warming and higher climate sensitivity.[403] Above 1,200 ppm CO_2, a "stratocumulus cloud deck evaporation" tipping point could raise global warming levels by an additional 8 °C.[404] Extreme heat and other impacts unleashed by these feedbacks pose systemic risks to human and natural systems,[405] including social, political, financial, and, ultimately, societal collapse (**Appendix B**).[406] Mapping of projected extreme heat to the Fragile State Index points to significant potential for conflict and vulnerability currently excluded from most economic analyses of social costs of climate pollution.[407]

In addition to potential tipping points in human systems, warming will abruptly shrink the habitable area for thousands of species over the span of a decade or two, likely causing mass extinction for species unable to rapidly migrate or evolve.[408] Even with a 1.5 °C overshoot where the temperature limit is only temporarily breached, some of the impacts will be irreversible, even if warming is later reduced.[409]

Figure 7. Climate tipping points



Source: Lenton T. M., Rockstrom J., Gaffney O., Rahmstorf S., Richardson K., Steffen W., & Schellnhuber H. J. (2019) *Climate tipping points—too risky to bet against*, Comment, NATURE, 575(7784): 592–595.

B. The Arctic is one of the weakest links in safeguarding our climate

The Arctic is critical for climate stabilization, yet it may be the weakest link in the chain of climate protection.[410] The Arctic's sea ice provides a "great white shield" that reflects incoming solar radiation safely back to space.[411] As the extent of the Arctic's reflective sea ice continues to shrink, the amount of heat going into the darker ocean increases. This, in turn, causes more ice to melt in a self-amplifying feedback loop,[412] and makes sea ice loss unavoidable for decades to come.[413]

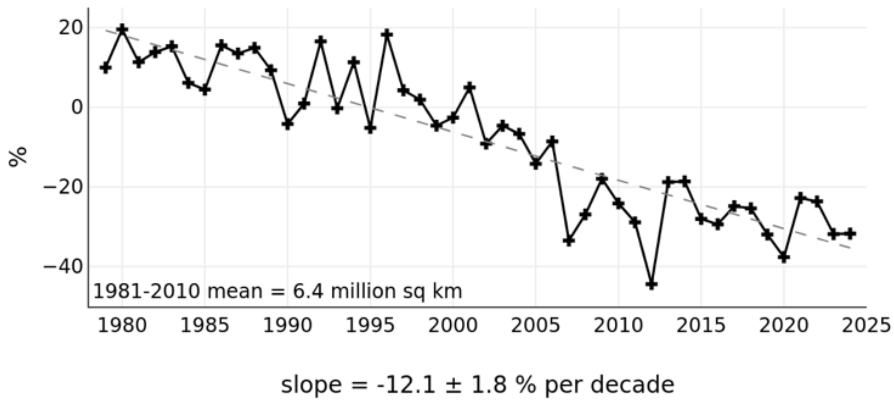
The Arctic air temperature is warming at a rate four times faster than the global average,[414] and the past decade has been the region's warmest on record.[415] Half of the Arctic's September sea ice is already gone,[416] and the rest could disappear within 10 to 15 years.[417]

If all of the Arctic sea ice were lost for the sunlit months, as could happen as early as mid-century,[418] it would add the warming equivalent of a trillion tons of CO_2, or 25 years of climate emissions at today's rate.[419] The Arctic's land-based snow and ice is also melting and is expected to add a similar amount of warming.[420] The intrusion of warmer ocean water from both the Atlantic[421] and the Pacific[422] is contributing to Arctic warming and the melting of the sea ice, intensifying the impacts of late summer cyclones and further accelerating sea ice loss.[423]

i. A rapidly warming Arctic

- Arctic air temperature is warming at a rate four times faster than the global average.[424]
    - Arctic mean surface temperatures may rise by up to 10 °C above the 1985–2014 average,[425] and in some regions up to 12 °C above the 1971–2000 average, by the end of the century.[426]
    - In 2020, Siberia experienced heat extremes that would have been "almost impossible" without human-caused global warming, including the first 100 °F (~38 °C) temperature recorded in the Arctic Circle. The record-breaking trends in the Arctic circle continued in the first half of 2021 with ground temperatures reaching 118 °F (~45 °C).[427]
    - The Arctic's "Last Ice Area," the Wandel Sea, saw unprecedented sea ice loss in August 2020 primarily due to abnormal weather patterns and warmth from the exposed ocean surfaces.[428] Summer sea ice in this area north of Greenland was thought to be more resilient and expected to persist decades longer than the rest of the Arctic,[429] providing a refuge for the region's ice-dependent flora and fauna.[430]
    - Between 1991–2020, surface air temperature in the Barents Sea area experienced record high annual warming of up to 2.7 °C per decade, with the Northern Barents Sea area warming at a rate 5–7 times the global warming averages.[431] During the warmer autumn season, the Northern Barents Sea area reached accelerated warming of up to 4.0 °C per decade between 2001–2020.[432]
    - As the Arctic heats up, warmer oceans melt more ice. Over the past 40 years, the Arctic Ocean has warmed at a rate of 0.5 °C per decade.[433]

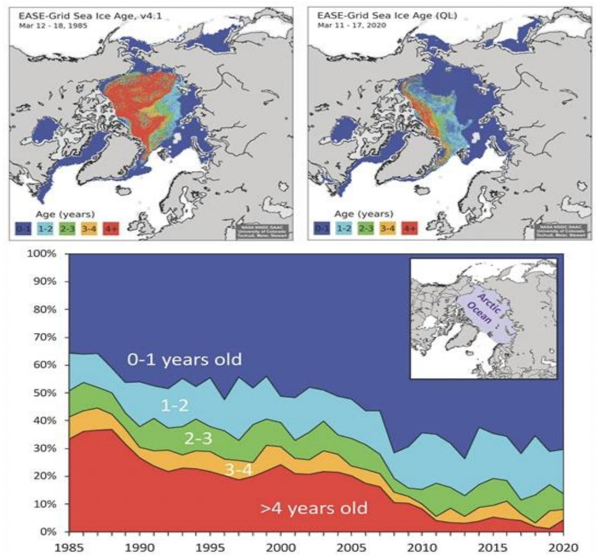
Figure 8. Monthly sea ice extent anomalies Sep 1979–2024



Source: National Snow and Ice Data Center, *Sea Ice Index*, Monthly Sea Ice Extent Anomaly Graph (*last visited* 22 January 2025) ("This graph shows monthly ice extent anomalies plotted as a time series of percent difference between the extent for the month in question and the mean for that month based on the January 1981 to December 2010 data. The anomaly data points are plotted as plus signs and the trend line is plotted with a dashed grey line.").

- The old "ecosystem of ice" in the Arctic no longer exists.[434]
    - Recent and current September sea ice extents are ~50% lower than when monitoring began in the 1980s,[435] with the risk that September will be ice-free within 10 to 15 years.[436] If all the Arctic sea ice were lost for the sunlit months, it would add the warming equivalent of a trillion tons of CO_2.[437]
    - Arctic sea ice reaches its minimum extent or coverage every September. Between 1982–2024, the September minimum extent decreased by approximately 12% per decade, creating a lost area of ice similar to the size of Alaska.[438]
    - In addition to extent, the thickness and volume of Arctic sea ice also decreased. Bewteen the September minimums of 1982–2020, sea ice *extent* decreased by 44% (from 7.6 million km^2 in 1982 to 4.3 million km^2 in 2020); sea ice *thickness* decreased by 48%; and sea ice *volume* decreased by 72%.[439]
    - The 18 Septembers with the least Arctic sea ice extent have all been in the last 18 years. In September 2024, the Arctic sea ice reached the seventh lowest extent since record-keeping began in 1979.[440]
    - The Arctic has lost 95% of its strong multi-year (>4 years old) Arctic sea ice since the 1980s. Young, first-year ice—which is thinner, more fragile, and more susceptible to decline—now comprises about 60% of the ice pack.[441]
    - In 2025, the Arctic winter sea ice pack reached its lowest recorded peak extent.[442]
- As the Arctic sea ice pack shrinks, it loses some of its ability to reflect sunlight safely back into the space, which contributes additional warming. Since 1980, the sea ice's radiative ability has weakened by 21–27%.[443]
- Land-based snow and ice in the Arctic is also melting and is expected to add a similar amount of warming to the trillion tons of CO_2 from losing the remaining sea ice for all sunlit months.

Figure 9. Late winter sea ice in the Arctic



Source: Perovich D., *et al.* (2020) *Sea Ice*, *in* ARCTIC REPORT CARD 2020, Thoman R. L., Richter-Menge J., & Druckenmiller M. L. (eds.), National Oceanic and Atmospheric Administration, 49 ("Fig. 3. Late winter sea ice age coverage map for the week of 12–18 March 1985 (upper left) and 11–17 March 2020 (upper right). Bottom: Sea ice age percentage within the Arctic Ocean for the week of 11–18 March 1985–2020. Data are from NSIDC (Tschudi et al. 2019, 2020).").

  - According to Dr. Peter Wadhams: "The loss of reflective land-based snow and ice is "of the same magnitude as the sea ice negative anomaly during the same period, and the change in albedo is roughly the same between snow-covered land and snow-free tundra as it is between sea ice and open water.… [T]he similarity of the magnitudes means that snowline retreat and sea ice retreat are each adding about the same amount to global warming."[444]
- Polar ice volume is a strong indicator of changes in the planet's fundamental climate state.[445] 2023 and 2024 broke records for glacial melt.[446]
  - Between the periods of 1992–1999 and 2010–2019, the rate of glacier and ice sheet loss increased by a factor of four.[447] Glacier mass loss and ice sheet mass loss were the largest contributors to sea level rise between 2002–2021.[448]
  - A study that combined satellite observations with numerical models found that, between 1994–2017, glaciers and ice sheets combined lost 28 trillion tons of ice as a result of global warming.[449] (One trillion tons of ice is equivalent to a cube of ice taller than Mount Everest.[450])
  - Globally, glaciers lost the equivalent of three Olympic swimming pools of ice every second (or 273 billion tons of ice per year) between 2000–2023.[451]

ii. Feedbacks from sea ice loss are supercharging Arctic warming amplification

- Arctic sea ice is declining at an accelerating rate.
  - The rate of decline in Arctic sea ice thickness from 2002 to 2018 may be underestimated by 60–100% in four of the seven marginal seas, according to a recent study using "snow data with more realistic variability and trends."[452]

- Warmer oceans are also accelerating sea ice loss, with warmer Atlantic[453] and Pacific[454] water transporting "unprecedented quantities of heat" into the Arctic Ocean, further reducing sea ice thickness. The warmer, saltier waters from the Atlantic Ocean are increasingly entering the Arctic in a process called "Atlantification of Arctic Ocean"[455] that is propagating northward. The strength of this warming is likely underestimated in CMIP6 models,[456] which were used by the IPCC in its AR6 reports.
- In the Northern Barents Sea, winter sea ice loss (due to warmer waters transporting heat from the Atlantic Ocean) is more pronounced. As subsurface water becomes warmer and saltier, it become buoyant enough to break through to the surface, and this weakened ocean stratification prevents the formation of sea ice.[457] Sea ice cover and ocean stratification in this region have been linked to abrupt changes during the last ice age.[458]
- With less sea ice in the Arctic Ocean, ocean waves can grow larger and accelerate ice breakup and retreat.[459] Late summer cyclones exacerbate this.[460] Arctic warming may also lead to a greater number of cyclones and to more intense cyclones,[461] creating a feedback loop of warming and sea ice loss.
- Exceptionally high winds in winter of 2020/21 drove multi-year ice into the Beaufort Sea,[462] "where ice increasingly can't survive the summer," resulting in record loss of the Arctic's multi-year ice.[463]

iii. We could lose our Arctic climate control by mid-century or sooner

- The Arctic could become consistently sea ice-free in September as soon as the 2030s, further reducing its heat-reflecting ability.[464] While the Arctic summer sea ice may not be a tipping system, continued melting of Arctic sea ice could cause a cascade of abrupt permafrost loss.[465] The loss of Arctic summer sea ice is a self-amplifying feedback loop and the ice will continue on its linear retreat as the Arctic continues to warm.[466]
  - Dansgaard-Oeschger events during the last ice age were associated with a rapid decline in Arctic sea ice that may have acted as a tipping point leading to changes in oceanic heat circulation, accompanied by a 2 to 3 °C rise in near-surface temperature over the Nordic sea.[467]
  - Ice-free conditions over multiple summer months likely occurred during the last interglacial period, providing further support for predictions of ice-free conditions in late summer by 2035.[468]
  - The Barents Sea and Greenland Sea could become ice-free year-round by the end of the century under high emissions scenarios.[469]
  - An ice-free September is already possible at current levels of warming and becomes likely at 1.8 °C of warming,[470] with the potential for accelerated ice loss as temperatures rise above 1.5 °C.[471] Limiting global warming to 2 °C or less could prevent the ice-free season from lengthening beyond September.[472]
- In the extreme case when all Arctic sea ice is lost for the sunlit months, as could happen as early as mid-century,[473] it would add the warming equivalent of 25 years' worth of current emissions—one trillion tons of CO_2—on top of the forcing from the 2.4 trillion tons of CO_2 emitted in the 270 years since the Industrial Revolution.[474]
  - This additional warming would be the equivalent of adding 56 ppm of CO_2 to the current CO_2 concentration.[475]

- The added forcing would be 0.71 W/m^2 averaged over the entire planet,[476] compared to the 2.16 W/m^2 added by anthropogenic emissions of CO_2 since the Industrial Revolution.[477]
- If all the cloud cover over the Arctic dissipates along with the loss of all sea ice, the added Arctic warming could be three times as much—the equivalent of three trillion tons of CO_2. In contrast, even if clouds increase to create completely overcast skies over the Arctic, the warming would still add the equivalent of 500 billion tons of CO_2 to the atmosphere.[478]

- Reduced Arctic snow cover is increasing the risk of wildfires, which emit black carbon, another super climate pollutant, while destroying sinks and emitting CO_2.[479]
  - Wildfires and permafrost thawing can "act together to expose and transfer permafrost C [carbon] to the atmosphere very rapidly."[480]
  - The "unprecedented" 2023 wildfires in North America burned over 11 million acres in and around the Arctic Circle and set a new record for area burned in Canada's Northwest Territories. The 2023 Canadian wildfire season produced over nine times more carbon than the 2003–2022 average,[481] an amount greater than Russia's yearly emissions.[482] Climate models project that by the 2050s, regional temperatures will be similar to those experienced in 2023,[483] which could increase the likelihood of similarly catastrophic wildfires.
  - The 2023 Canadian wildfires are an example of a self-amplifying feedback loop: made more likely and more intense by anthropogenic global warming,[484] they release additional carbon into the atmosphere, ensuring that warming will continue to increase.
- Additional factors contribute to further snow and ice loss in the Arctic.
  - The warming Arctic has also experienced three times more lightning in the last decade,[485] igniting more fires and threatening to accelerate permafrost thaw.[486] Boreal fires which smolder in organic soils and remerge after months, called "zombie fires" or "overwintering fires," emitted about 3.5 million metric tons (Mt) of carbon between 2002 and 2018.[487]
  - Rapid melting in the Arctic opens up new shipping lanes, which trigger further pollution and warming as increased shipping traffic, oil and gas exploration, and tourism burns heavy fuel oil and emits black carbon.[488] From 2009–2018, shipping activity in the Norwegian Exclusive Economic Zone increased by 42%.[489] Increased Arctic shipping lanes also introduce geopolitical problems and other evolving security risks.[490]

C. A critical shift may already be underway in the Antarctic

Like the Arctic, the Antarctic provides the planet's climate control, acting as a "refrigerator" that keeps the world from overheating. Recent large-scale abrupt changes, such as record-breaking sea ice declines in recent years,[491] along with the catastrophic loss of ice shelves (such as Larsen B), suggest that the Antarctic refrigerator may be defrosting.[492]

As in the Arctic, Antarctic sea ice is critical for reflecting sunlight back into space. The loss of Antarctic sea ice is another feedback loop that contributes to warming by reducing reflection of sunlight, and may be contributing to the increasing positive imbalance in the Earth's energy budget (Earth's Energy Imbalance, EEI).[493] Unlike grounded glacier ice, sea ice does not directly contribute to sea level rise. However, as sea ice provides critical buttressing for the ice sheet that it surrounds,[494] changes to its behavior could affect the stability of the whole ice sheet.

- In March 2022, the East Antarctic region experienced the most extreme heatwave ever recorded globally, reaching 38.5 °C (69.3 °F) above its average temperature.[495] This is associated with an "atmospheric river" that transports heat and moisture from the subtropics into the Antarctic.[496]
  - In July 2024, another record heatwave boosted the monthly average temperatures more than 10 °C (18 °F) above average, with at least one day reaching 28 °C (50 °F) above average, raising the potential for the collapse of ice sheets.[497]
- Precipitously low sea ice extents in recent years have scientists questioning if a major "regime shift" may already be underway.[498]
  - The decline of Antarctic sea ice since 2016 has diminished the amount of solar radiation that it can safely deflect back to space by as much as 14%.[499]
  - The past four Antarctic summer seasons (2022–2025) were the four lowest sea ice extents on record.[500]
  - In addition to summer extremes, during the Antarctic winter of 2023, sea ice reached the lowest maximum extent observed in the 45-year monitoring program.[501] In July 2023, the area of "missing" ice was the size of Argentina (~2.8 million km^2).[502] Absent global warming, such an extreme low would likely occur only once every several million years,[503] but such extremes are "now virtually certain to continue."[504]
  - During the 2024 winter, the sea ice regrew beyond the 2023 minimum, but was still over 1.5 million km^2 below the 1981–2010 average.[505] These two years of record lows suggest that Antarctica sea has entered a new state.[506]

Diminishing sea ice and warming oceans also accelerate the melting of *ice shelves*. Warmer waters melt floating ice shelves from below, destabilizing these protective "ice tongues" that *buttress* the grounded ice sheet. Ice shelf buttressing prevents the land-based glaciers that make up an ice sheet from slipping into the ocean, raising sea levels. Recent observations in the Antarctic show a trend of extreme warming and the "retreat, thinning and disintegration" of ice shelves, which form 75% of Antarctica's coastline and act to stabilize the rate of ice flow from the grounded ice sheets.[507]

- Between 2009–2019, the West Antarctic ice shelves lost 5.5% (5,500 km^2) of area due to calving and retreat.[508]
- Widespread meltwater ponding on the surface of ice shelves contributes to loss; "the collapse of the Larsen B Ice Shelf was triggered by widespread meltwater ponding on the ice shelf surface where crevasse hydrofractures caused pressure-driven disintegration of the shelf in a matter of days. … If such events become more frequent in a warming climate further incidences of ice shelf disintegration may occur." [509]

In West Antarctica, the Thwaites glacier is buttressed by ice shelves that are vulnerable to warming from the nearby Amundsen Sea.

- Losing the Thwaites glacier, which is currently the size of Florida or Britain, could raise sea levels by over two feet (65 cm).[510] Once the Thwaites glacier retreats past a ridge 50 km upstream, the self-amplifying retreat would "become unstoppable."[511]

- The Thwaites glacier is already contributing to 4% of sea level rise.[512] In the last 20 years, the glacier has retreated by over a kilometer every year,[513] has lost more than 1,000 billion tons of ice, and continues to lose ice at a rapidly increasing rate.[514]
- Thinning of the Thwaites glacier appears to have accelerated since 2009.[515] Recent studies warn that the Thwaites glacier is melting faster than historically observed, and that a similar pace of rapid melt could occur in the future.[516]
- One glaciologist found that the ice shelf buttressing the Thwaites glacier could collapse in as little as three years due to massive fractures caused by the intrusion of warmer ocean water, setting off a "chain-reaction" that could eventually add 2 to 10 feet of sea level rise over centuries.[517]
- The icefront of Thwaites is also retreating due to ice calving, which can trigger further melting and instability. A catastrophic calving event would lead to greater, more immediate sea level rise than that caused by ice shelf thinning alone.[518]
- By 2100, Amundsen Sea in West Antarctica could be up to 2 °C warmer than pre-industrial temperatures, a significant increase for Antarctic water masses, with committed melting is likely even if the Paris 1.5 °C target is maintained.[519]
    - Warmer waters appear to have contributed to the irreversible retreat of Thwaites' neighbor, the Pine Island glacier, which was responsible for 13% of Antarctica's mass loss between the 1970s and 1990s.[520]

D. The approaching ice sheet tipping points

Several climate tipping points are at risk if warming exceeds 1.5 °C for more than several decades. The Greenland Ice Sheet and West Antarctic Ice Sheet both show signs of approaching tipping thresholds, estimated around 1.5–2 °C.[521] Once triggered, significant ice loss is irreversible even if CO_2 removal strategies are successful.[522] Between 2011–2020, the Greenland and Antarctic Ice Sheets lost a combined 38% more mass compared to the decade before (2001–2010), providing further evidence that the rate of ice loss has increased since the 1990s.[523]

Taken together, the ice sheets of Greenland and West Antarctica could produce 10 meters of sea level rise over the coming centuries if their approaching tipping thresholds are crossed.[524] The fates of the Greenland and West Antarctica Ice Sheets are linked: tipping of either ice sheet could tip the other,[525] and could also trigger a shutdown of the Atlantic Meridional Overturning Circulation (AMOC).[526]

i. The West Antarctic Ice Sheet is destabilizing

- Best estimates of the West Antarctic Ice Sheet's tipping point put its critical threshold between 1–3 °C.[527]
    - Even if the Paris Agreement 1.5 °C target is met, the rate of ocean warming in the West Antarctic is projected to triple by the end of the century, accompanied by significant increases in the rate of ice shelf loss.[528] Current levels of warming may already be enough to lock-in loss of much the West Antarctic ice sheet.[529]
    - A recent, higher-resolution model of the Antarctic Ice Sheet and surrounding ice shelves indicates that (in agreement with satellite observations) past assessments may underestimate Antarctic melting by 45% and that yearly melting rates may increase ten times by 2100 under a high-emissions scenario.[530] Researchers

estimated that, since 2002, the Antarctic Ice Sheet has already at least contributed 6.3 mm to sea level rise, mostly from the West Antarctic region.[531]

  - Short periods of fast ice retreat, up to 30 meters per day, have been observed in the satellite record. Paleoclimate evidence shows similarly extreme rates of retreat in the distant past, suggesting that projections of the ice sheet's future retreat are underestimates.[532] Abrupt changes like these, triggered by extreme weather events, could start the ice sheet on a self-sustaining feedback loop,[533] potentially driving it over its tipping point.

ii. The Greenland Ice Sheet is melting at an accelerating rate

- The melting Greenland Ice Sheet is already the largest single contributor to the rate of global sea level rise,[534] and is expected to lose 110 trillion tons of ice by the end of the century, which would raise global sea levels by nearly a foot (27 cm).[535]
  - Recent observations show that the rate of retreat was as high as 610 m per day during the last interglacial period, and current levels of ocean-driven melting can trigger 100 m of ice sheet loss each day.[536]
  - AR6 WGI was unable to exclude the possibility of sea level rise of up to 7.5 feet (2.3 m) by 2100 due to uncertainties in ice sheet processes.[537]
  - Early warning signs suggest that the Greenland Ice Sheet is close to a tipping point.[538] Currently, the best estimate of the threshold for irreversible melting of the Greenland Ice Sheet is around 1.5 °C (with a range of 0.8–3 °C).[539]
  - In the past two decades, the melt rate across Greenland increased 250–575%, and the ice discharge from the Greenland Ice Sheet substantially increased. [540] This will likely persist in the coming years.[541] Ice caps and outlying glaciers, which represent a small part of Greenland's ice-covered area but disproportionately contribute to its total ice loss, are retreating nearly twice as fast in the 21st century as they did in the 20th century.[542]
  - North Greenland's ice shelves have lost over 35% of their volume and one-third of their area since 1978; three have collapsed completely.[543] Continued ocean warming is likely to weaken these ice shelves and their ability to buttress the North Greenland glaciers, which represent 2.1 meters of possible sea level rise.[544]
  - Driven by that year's global heatwaves, 2023 was the fifth time on record that Greenland's Summit station, the highest point on the ice sheet, witnessed melting.[545]
  - In July 2021, Greenland experienced a massive melt event that alone would be enough to cover the state of Florida with two inches of water.[546]
  - In August 2021, rainfall occurred at the highest point on the Greenland Ice Sheet, which has never been recorded before at that location (72.58°N 38.46°W).[547] Since the 1990s, the amount and frequency of rainfall on the Greenland Ice Sheet has increased; rain may seep into the ice sheet via small cracks and increase melting.[548]
- If all of Greenland melted, it would contribute up to 7 meters of sea level rise.[549]
  - While fully melting the Greenland Ice Sheet would take millennia, the rate of future melt, and thus rate of sea level rise, depends "strongly on the magnitude and duration" of overshooting the tipping threshold.[550]
  - The ice sheet collapse could be avoided during an overshoot period of decades to centuries.[551] One recent climate modeling study indicated that the ice sheet can be

substantially preserved in its current state with a century-long overshoot of several degrees, provided that the regional temperature is brought below the critical threshold within another hundred years.[552] However, meltwater from the ice sheet could still contribute significantly (>1 meter) to sea level rise.[553]

- Continued melting of the Greenland Ice Sheet could facilitate a tipping cascade with the Atlantic Meridional Overturning Circulation (AMOC), by both pushing AMOC past its tipping threshold and preventing the ice sheet's own recovery—despite cooler temperatures induced by AMOC shutdown.[554]

E. The Atlantic Meridional Overturning Circulation is weakening

The Atlantic Meridional Overturning Circulation (AMOC) is the branch of the ocean's "global conveyor belt" that circulates life-sustaining water, heat, and nutrients throughout the Atlantic Ocean. The AMOC transports warm water from the tropics to polar regions, where the water loses heat and becomes denser, sinking to form a deeper current. As the waters return south, they are warmed and returned to the surface, closing the loop. This process (known as *thermohaline circulation*) is also driven by differences between saltier, heavier water and fresher, lighter water.

- Over the past 70 years, the AMOC has weakened by approximately 10%.[555]
    - The continued weakening of the AMOC over the course of the 20th and 21st centuries raises concerns[556] that it could pass a tipping point to a much slower circulation mode.[557] This would have dire consequences for regional and global climate.
    - As snow, sea ice, and ice sheets melt due to global warming, ocean waters become less salty and less dense, which can cause the AMOC to slow.[558] This can create a self-amplifying feedback loop in which a slower AMOC transports less salt to the North Atlantic, and this fresher AMOC slows further, until the circulation passes a tipping point and is unable to recover.[559]
- Paleographic data from ice cores and sediments provide evidence that AMOC underwent abrupt transitions in the past.[560]
    - Climate models show that the AMOC can tip due to an influx of freshwater,[561] which could come from melting ice sheets in Greenland or Antarctica.[562]
    - A higher rate of freshwater entering the North Atlantic might also tip the AMOC into a weaker circulation pattern, faster than expected.[563]
- According to AR6 WGI, it is "very likely" that the AMOC will weaken in the 21st century, with *medium confidence* that it will not collapse by 2100.[564]
    - However, current models may be biased in favor of a stable AMOC,[565] failing to accurately capture relationships between the AMOC, ice sheets, and other global tipping elements.[566]
    - Two recent studies agree in their estimate that the AMOC may collapse as early as the 2050s, but the uncertainties remain relatively high.[567] Models may also dangerously underestimate the likelihood of tipping point cascades initiated by one element, such as the Greenland Ice Sheet, which has its own tipping point at or around 1.5 °C.[568]

- A dramatic weakening or complete shutdown of the AMOC would shift weather patterns around the world, [569] with devastating changes occurring so rapidly that societies would find it difficult, if not impossible, to adapt.
    - AMOC shutdown would imperil food and water security for more than half of the world's population by triggering irreversible shifts in the timing and wetness of monsoons in the Amazon, West Africa, India, and East Asia, along with drastic cooling across parts of Europe (up to 3.5°C per decade).[570]
    - A weakened circulation would also drive faster sea level rise along parts of the Eastern United States (an added 6–8 inches)[571] and Europe, stronger hurricanes in the Southeastern United States, and reduced rainfall across the Sahel.[572]

In October 2024, more than 40 climate scientists signed an open letter to the Nordic Council of Ministers, drawing attention to the "greatly underestimated" risk of AMOC collapse.[573] The scientists urged Nordic leaders to carry out a risk assessment of AMOC collapse and encouraged them to "increase pressure" on other governments to reduce emissions in line with the 1.5 °C guardrail.[574]

While the likelihood and timing of AMOC collapse remain uncertain, "[g]iven the impacts, the risk of an AMOC collapse is something to be avoided at all cost."[575]

F. Permafrost thaw feedback could rival major emitters for CO_2, CH_4, and N_2O

As the Arctic continues to warm at four times the global average,[576] Arctic permafrost is beginning to thaw and release its long-held sink of greenhouse gases.[577] This could set off a self-amplifying feedback loop that could release 110 to more than 550 Gt CO_2 this century,[578] rivaling the cumulative emissions from the United States at its current rate (approximately 400 $GtCO_2$ based on current emissions of about 5 $GtCO_2$ per year).[579] By 2100, this feedback loop could contribute additional warming of 0.05–0.7 °C, with permafrost methane contributing up to 50% of the radiative forcing driving this warming.[580]

- Permafrost contains nearly twice the amount of carbon than is already in the atmosphere,[581] and accounts for one-third of all the world's carbon stored in soils.[582] As it thaws, it releases ancient stores of CO_2, methane,[583] and N_2O[584] (which also destroys stratospheric ozone).
- Yet more than 80% of IPCC models do not include climate emissions from permafrost thaw.[585]
- Current levels of warming have already locked in yearly permafrost thaw emissions that rival Japan's.[586] This number will only grow as warming is virtually certain to increase in the short-term.
- Arctic permafrost at high latitudes has warmed at a rate up to of 1 °C per decade since the 1980s.[587] AR6 WGI calculates that for each °C of global warming at 2100, the permafrost feedback could release 66 $GtCO_2$ (11 to 150) and 10 $GtCO_2e$ (2.6 to 27) of methane, in addition to N_2O, which most estimates do not account for.[588]
- Holding the global temperature to the 1.5 °C Paris guardrail could generate 30–50% less permafrost emissions by 2100 than the higher 2 °C target.[589]
- In addition, up to 20% of the permafrost area accounting for half of permafrost carbon could experience abrupt local thaw events,[590] such as the formation of thermokarst lakes.

Regionally, these abrupt events can act as tipping points that increase pressure on other parts of the climate system.[591]

- Abrupt thaw events could cumulatively emit up to nearly 11 Gt carbon in the form of CO_2 (40 Gt CO_2) and 6.8 Gt carbon in the form of methane (9 Gt CH_4) by 2100, in addition to the 92 Gt carbon that could be released by gradual thaw over this period under a high-emission scenario.[592]
- Models that consider only gradual thaw underestimate permafrost carbon emissions by 40% through 2300.[593]
- "[U]p to half of recent permafrost thaw has occurred during extreme heat events of up to 12 °C above average, as a result of "abrupt thaw" processes where coastlines or hillsides collapse, or lakes form; exposing much deeper and greater amounts of permafrost to thaw."[594]
- Some of the emissions from thawing permafrost are expected to be offset by the expanded growth of biomass, but only if human emissions are curbed.[595]

- In addition to accelerating soil carbon feedbacks due to permafrost thaw, heatwaves in the Siberian Arctic (such as those in 2020 that peaked at 6 °C above normal temperatures) may be causing "surprise" fossil methane gas to leak from rock formations.[596]
- The increasing Arctic wildfires are accelerating permafrost thaw,[597] and may become "a dominant source of Arctic carbon emissions during the coming decades."[598]
  - Permafrost thaw and wildfires could create a self-sustaining feedback loop: as Arctic permafrost warms, it also dries out, with wildfire events predicted to increase abruptly after mid-century as this happens.[599]
- Other factors contributing to permafrost thaw and release of carbon stocks are increased rainfall in the Arctic region[600] and coastal erosion from sea level rise[601] and sea ice loss.[602]
- Thawing permafrost also impairs human settlements and health.[603]
  - About 3.3 million people, 42% of settlements, and 70% of current infrastructure in the permafrost is at risk of severe damage due to permafrost thaw by 2050, including 45% of oil and gas production fields in the Russian Arctic.[604] Damage to Russian infrastructure alone due to permafrost thaw could cost US$69 billion by 2050.[605]
  - By 2085, the costs of maintaining permafrost-based infrastructure in the Northern Hemisphere (including both the Arctic and the Qinghai-Tibet plateau) could be as high as US$205–572 billion, if emissions are not reduced.[606] The same study projected that a pathway of robust emissions cuts would reduce by ~10% the area of permafrost exposed to medium-high hazards by 2085.[607]
  - Thousands of industrial sites in the Arctic, which contain uncharacterized pathogens, risk mobilization of legacy contamination due to warming and thawing permafrost.[608] Pollutants can be released from mining tailings as well as from landfills for municipal waste.[609]

G. An additional methane threat is lurking on the East Siberian Arctic Shelf

Another risk is that warming ocean waters will destabilize seabed methane hydrates.[610] Such destabilization likely occurred off the coast of Guinea 125,000 years ago during the previous interglacial, with ice core records suggesting that a sufficient amount of methane was released to the atmosphere to affect CO_2 and methane concentrations.[611] With a rapidly warming Arctic, the shallow seabed of the East Siberian Arctic Shelf poses significant risk due to its potential to speed up other global warming impacts.[612] Although there is debate on the rate of potential release,[613] the rate of methane release in the Chukchi Sea was higher in 2010s compared to 1990s.[614] Release of land-based methane hydrates as glaciers recede could further amplify the permafrost feedback.[615]

- Measurements in October 2020 by an international expedition on a Russian research vessel showed elevated methane release from the Arctic Shelf, according to Jonathan Watts in *The Guardian*.[616] The story quotes Swedish scientist Örjan Gustafsson of Stockholm University, stating that the "East Siberian slope methane hydrate system has been perturbed and the process will be ongoing." Analysis of elevated methane measured in the area in 2014 suggest a fossil methane source beneath the seabed that "may be more eruptive in nature."[617]
- According to an earlier isotopic analysis of methane from an Antarctic ice core record, up to 27% of methane emissions during the last deglaciation may have come from old carbon reservoirs of permafrost and hydrates; while this "serves only as a partial analog to current anthropogenic warming," the authors stated that it is "unlikely" that today's anthropogenic warming will release the carbon in these old reservoirs.[618] At least one set of climate models has assessed the store of methane hydrates under in the East Siberian Arctic to be largely stable over geological timescales.[619]

H. The ocean is a heat battery

At the end of 2024, the ocean was hotter than ever.[620] Compounding the risk from self-amplifying feedbacks and tipping points, ocean warming will continue well after emissions stop. About 93% of the energy imbalance accumulates in the oceans as increased heat,[621] which will return to the atmosphere on a timescale of decades to centuries after emissions stop.[622] Ocean warming has accelerated since the 1960s:[623] by 2003–2018, the rate of ocean warming increased tenfold from 1958–1973 levels.[624] The pace at which heat accumulates in the upper layers of the ocean may be accelerating.[625] As reported in AR6 WGI:

> "It is *virtually certain* that the global ocean has warmed since at least 1971, representing about 90% of the increase in the global energy inventory… and is currently warming faster than at any other time since at least the last deglacial transition (*medium confidence*). It is *extremely likely* that human influence was the main driver of ocean warming. Ocean warming will continue over the 21st century (*virtually certain*) … [and] is irreversible over centuries to millennia (*medium confidence*)."[626]

6. Conclusion

The extreme temperatures and weather events of 2023 and 2024 demonstrate the harsh realities that await us in a 1.5 °C world and show that there is no time to waste in slowing near-term warming impacts. Global warming is projected to cross the 1.5 °C guardrail by the end of this decade or sooner. Policies that rely on decarbonization alone are insufficient to slow the near-term warming to keep the planet below 1.5 °C or even below the more dangerous 2.0 °C threshold.

We need to urgently broaden our approach to climate mitigation to target both CO_2 and other largely neglected super climate pollutants to address the near-term and long-term impacts of climate disruption, avoid or at least delay irreversible tipping points, and maintain a livable planet.[627]

Combining efforts to cut CO_2 emissions by decarbonizing the energy system *with* mitigation measures targeting non-CO_2 super climate pollutants methane, HFC refrigerants, black carbon soot, and ground-level ozone smog, as well as nitrous oxide, would reduce the rate of warming by half over the next two decades, which would slow the rate of warming a decade or two earlier than decarbonization alone *making it possible for the world to keep the 1.5°C guardrail in reach*[628] *and avoid or delay triggering a cascade of tipping points*.[629] This strategy of a sprint this decade to slow warming in the near term by cutting super climate pollutants and protecting carbon sinks through nature-based solutions complements the marathon to reach net zero CO_2 emissions by 2050 to stabilize temperatures in the longer term.[630]

As UN Secretary-General António Guterres said, AR6 is a "code red" for the climate emergency.[631] The IPCC's 2018 *Special Report on 1.5 °C* presented the three essential strategies for keeping the planet relatively safe: reducing CO_2, which is a marathon, reducing super climate pollutants, which is a sprint, and removing up to 1 trillion tons of CO_2 from the atmosphere by 2100, an ultra marathon.[632] Cutting super climate pollutants is the only known strategy that can slow warming and feedbacks in time to avoid catastrophic and perhaps existential impacts[633] from Hothouse Earth,[634] other than perhaps solar radiation management, which carries its own risks and governance challenges.[635]

Appendix A. Types of temperature and warming as defined by the IPCC and others

The IPCC differentiates among five kinds of temperature/warming:[636]

1) Observed global average *annual* temperature (varies year-to-year due to internal variability and weather patterns, such as the El Niño Southern Oscillation).

- 2024 marked the first time where global temperatures breached the 1.5 °C threshold for an entire calendar year, averaging 1.55 °C across different datasets.[637]
- In June 2024, the World Meteorological Organization (WMO) forecasted an 80% chance that the global annual temperature will exceed 1.5 °C for at least one year between 2024 and 2028, and a 47% chance that the five-year mean from 2024–2028 will exceed this threshold.[638] This indicates that it is "as likely as not" that the global temperature will—even if temporarily—exceed the 1.5 °C guardrail.

2) *Current total warming* (observed change) in global average temperature is the annual temperature averaged over the preceding 10 or 20 years and includes both natural and anthropogenic components.

- Average observed warming between 2004–2023 was 1.05 °C above 1850–1900 baseline levels.[639] Between 2015–2024, average observed warming was about 1.25 °C higher than the 1850–1900 baseline.[640]
- "Each of the last four decades has been successively warmer than any decade that preceded it since 1850."[641]

3) *Current human-induced global warming* is averaged over the preceding 10 years is the component of total warming attributable to human activities.

- The 10-year average *current human-induced global warming* over 2014–2023 was 1.19 °C higher than pre-industrial.[642] Warming over this period increased at an unprecedented rate of over 0.26 °C per decade, [643] compared to the 0.2 °C per decade trend of the past 40 years.[644]
- Human-induced global warming is responsible for essentially all observed warming.[645]

4) *Current single-year human-induced global warming* is averaged over 30 years centered on the current year, while projecting the next 15 years using a constant rate of warming.

- In 2023, the single-year human-induced global warming was 1.31 °C, breaching the 1.3 °C threshold for the first time.[646]

5) Reaching a *future* level of global warming is defined by the IPCC in AR6 as the midpoint of the first 20-year period when average global surface air temperature change exceeds a particular level of global warming, based on scenario projections that include an accelerated rate of warming in the near term.[647]

- There is a 50% probability that 1.5 °C has been crossed once the observed mean for the most recent 11-years reaches 1.43 °C and 90% at 1.44 °C, but these likelihoods are an underestimate if rates of warming accelerate.[648]

- According to the *2024 UNEP Emissions Gap Report*, under current policies global temperatures are on track to reach 2.6 °C [1.8–3.4 °C] of peak warming this century.[649] This is consistent with the range projected by the AR6 Synthesis Report, which also noted that if climate sensitivity or climate feedbacks are higher, warming levels could exceed 4 °C.[650] Recent work by Hansen *et al.* concludes that the climate may be even more sensitive to climate forcing than previously thought, implying that there may be more warming in the "pipeline" than expected, which "will exceed 1.5°C in the 2020s and 2°C before 2050," and eventually reach an equilibrium warming of 8–10 °C in later centuries.[651] While not directly comparable to the equilibrium climate sensitivity, the apparent Earth System Sensitivity was recently estimated for the past 485 million years as about 8 °C.[652]
- Even assuming continued emissions, model projections may underestimate the future rate of warming by up to 60%.[653]

Appendix B. Current and future impacts from extreme heat

According to AR6 WGI, "[i]t is *virtually certain* that hot extremes (including heatwaves) have become more frequent and more intense across most land regions since the 1950s… with *high confidence* that human-induced climate change is the main driver of these changes."[654]

- Extreme heat affected billions of people across Asia in April 2024, with temperatures rising above 40 °C.[655] Human-caused climate change made this heatwave five more times likely in West Asia and up to 45 times more likely in South Asia.[656] Extreme heat continued to affect parts of Asia in May 2024, with temperatures reaching above 49 °C.[657]
- In February 2024, the southern coastal zone of West Africa experienced an unseasonably early and record-breaking humid heatwave, reaching levels of "extreme danger" for heat stroke in parts of the region.[658] This event was made ten times more likely and 4 °C warmer due to human-induced global warming.[659]
- As of 2023, the occurrence of yearly local humid-heat is increasing by more than four days every decade. If 2023-like heat conditions reoccur the future, producing similar numbers of anomalously humid-hot days, this additional contribution would mean that the world would experience more than 38 days of locally extreme conditions every year by 2050.[660]
- Between June and August 2023, 3.8 billion people experienced at least one month of extreme heat made three times more likely by global warming.[661]
- The July 2023 heatwave in the U.S., Mexico, and Southern Europe, which broke global heat records for four days in a row,[662] would have been "virtually impossible" without human-driven global warming.[663] Temperatures above 50 °C broke records in North African cities.[664]
- The 2022 record-breaking early season heatwaves in Argentina and Paraguay were made 60 times more likely due to anthropogenic climate change.[665] These heatwaves increased wildfires in Argentina and Paraguay by 283% and 258% at the beginning of 2022.[666]
- In 2022, unprecedented heatwaves affected nearly 2 billion people in India and Pakistan, with scientists noting that "the current climate has changed so significantly that the pre-industrial world becomes a poor basis of comparison."[667] Future heat stress exposure will be exacerbated by existing global income inequalities, with the bottom quarter of low-income countries expected to experience "almost as much exposure to heatwaves" as the rest of the world combined by the 2090s.[668]
- The 2021 heatwave in western Canada and the northwest U.S. would have been virtually impossible absent human-induced global warming, and in a 2°C world would occur every 5 to 10 years.[669]
- Over the next 20 years (2021–2040), one-fifth of the world's population could be exposed to an unprecedented acceleration in the rate of temperature extremes.[670] While this risk can be reduced under a low-emissions pathway,[671] countries in Southern Asia and the Arabian Peninsula will still see higher rates of climate extremes.[672]
- By 2053, an "extreme heat belt" affecting over 100 million people is expected to form in the central U.S., where temperatures will exceed 125 °F (~52 °C) at least once a year.[673]

- Urban heat islands magnify extreme heat risks for city-dwellers.[674] By 2050, rising temperatures will expose eight times more urban people living in poverty to extreme heat, especially in West Africa and Southeast Asia.[675]
- Future humid heatwaves will compromise the ability of humans to cope with extreme heat, particularly in the highly populated areas of eastern China, the Indus River Valley, and Sub-Saharan Africa.[676] An estimated 5 billion people may experience severe humid heat-stress impacts by the end of the century if Paris-level warming goals are not met.[677]
- Heat and humidity will compromise agricultural workforce capacity, even under moderate-emission scenarios. By 2100, with almost one-third of laborers working at a physical capacity of 60% or less during the growing season.[678]
- At a warming level of 1 °C, which the planet has already passed, an estimated 8 million people may have half of their yearly work hours restricted because conditions are too hot for outdoor work. Warming of 2 °C could increase this to nearly 800 million people by 2050.[679]
- Extreme heat led to a global loss of US$ 863 billion in 2022 alone, and this number is projected to skyrocket to US$ 2.4 trillion by 2030, with low- and lower-middle-income countries shouldering a large and unequal share of losses.[680]
- At 4 °C of warming, an estimated 2.7 billion people worldwide could be exposed to dangerous wet-bulb temperatures of 31 °C or more for one week every year.[681]
- The tropics will see appreciably higher temperatures than the global average even if the global warming is kept within the 1.5 °C and 2 °C guardrails.[682] However, limiting warming to 1.5 °C would prevent most of the tropics from exceeding the combined heat and humidity conditions beyond the survival limit.[683] In contrast, warming of 2.7 °C by the end of the century would leave about a third of the global population outside of the human climate niche (2 to 2.5 billion people), while limiting warming to 1.5 °C would reduce this by half.[684]

Appendix C. Recent trends in greenhouse gas concentrations in the atmosphere

The *rate of warming* is increasing, due to increasing atmospheric concentrations of CO_2 and other climate pollutants, the reduced ability of oceans to store warming, and the reduced albedo from the loss of reflective snow and ice and clouds.

- The *rate of CO_2 concentrations* in the atmosphere is currently increasing at least 10 times faster than at any other time during the last 800,000 years.[685]
- This increase in CO_2 is being driven by continuing emissions and an apparent slowing of the ocean and terrestrial sinks, which typically take up 50% of CO_2 emissions.
  - The rate of CO_2 sequestration by forests and other aspects of the terrestrial carbon sink peaked in 2008 and the terrestrial sink has been declining ever since,[686] leaving more CO_2 to accumulate in the atmosphere at a more rapid rate.
  - "Climate conditions reduced the land sink by an estimated 27% in the past decade due to warming and reduced rainfall," according to the 2024 Global Carbon Budget.[687]
  - The ocean sink also appears to be shrinking; the ocean historically has taken up about 30% of anthropogenic CO_2 emissions, but is losing its ability to sequester CO_2 as warming progresses.
- The ocean also appear to be losing its ability to sequester heat;[688] historically the ocean has stored around 90% of warming.[689]
- The reduced albedo, or reflectivity, from the loss of snow and ice and clouds also is adding to the rate of warming, as these reflective surfaces are replaced with darker land and oceans that absorb more warming.
- Under the carbon budget approach, there is only 235 $GtCO_2$ remaining for a 50% chance of limiting warming to 1.5 °C; at the current rate of emission the 1.5 °C budget will be consistently exceeded in six years.[690]

Figure 10. Trends in CO_2, CH_4, and N_2O concentrations in the atmosphere

	Absolute atmospheric concentration			***Growth rate (per year)***			
	2022	**2023**	**2024**	**2001–2010 average**	**2011–2020 average**	**2020–2023 average**	**2024**
CO_2 (ppm)	417.1	419.4	422.8	2.0	2.4	2.4	3.8
CH_4 (ppb)	1910.9	1921.6	1930.1	2.9	8.5	13.5	9.5
N_2O (ppb)	335.6	336.7	337.7	0.8	1.0	1.2	1.0

ppm = parts per million, ppb = parts per billion

Source: National Oceanic and Atmospheric Administration, *Global Monitoring Laboratory - Carbon Cycle Greenhouse Gases* (2025).

Glossary

Carbon budget	Also *remaining carbon budget.* The amount of carbon dioxide that can still be emitted, for a given likelihood (often 50% or 67%), of remaining below a specific global warming level (such as 1.5 °C or 2 °C). However, the carbon budget methodology is limited by modeling uncertainties,[691] including built-in assumptions that reductions in non-CO_2 pollutants will take place.[692] It therefore cannot be used to estimate a "remaining emissions budget" for non-CO_2 pollutants like methane.
Carbon sink	Anything that absorbs more carbon dioxide than it emits (i.e., removes and stores carbon dioxide from the atmosphere). Examples of natural carbon sinks include oceans, forests, peat bogs, mangroves, seagrass beds, kelp forests, salt marshes and swamps.
Carbon source	Anything that releases more carbon dioxide than it absorbs. Examples of carbon sources include emissions associated with fossil fuel extraction and combustion, as well as deforestation.
Earth's Energy Imbalance (EEI)	The difference between the amount of solar energy absorbed by Earth and the amount of energy that the planet radiates back to space as heat. The current positive energy imbalance means that the Earth system is gaining energy, causing the planet to heat up. Increases in greenhouse gases and decreases of cooling aerosols both increase EEI.
Intergovernmental Panel on Climate Change (IPCC)	The IPCC was established in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP), and endorsed by a UN General Assembly resolution in 1988. The IPCC prepares a comprehensive review and recommendations with respect to the state of knowledge of the science of climate change and the social and economic impact of climate change. Since its inception, the IPCC has prepared six Assessment Reports.
Overshoot	Global warming that temporarily breaches 1.5 °C above pre-industrial levels. Even with overshoot, some impacts could still be irreversible, even if global warming is later reduced. The *magnitude* and *duration of overshoot* is generally taken to mean the peak amount of warming by which the 1.5 °C limit is exceeded (*magnitude*) and the length of time that the temperature remains above 1.5 °C before it is brought back to 1.5 °C or lower (*duration*).
Radiative forcing	The Earth's response to a difference between the amount of energy (*radiation*) entering the atmosphere and the amount that leaves. The accumulation of greenhouse gases and aerosols in the atmosphere prevents energy from leaving; this *forces* a change in the Earth system, which responds with an increase in temperature. Clouds, snow and ice extent, and vegetation cover also affect radiative forcing. Over the years, the IPCC has used different representations of radiative forcing (RF) in its Assessment Reports, including effective radiative forcing (ERF), instantaneous radiative forcing (IRF), and stratospheric temperature-adjusted radiative forcing (SARF). These have slightly different definitions and applications.
Paris Agreement	The Paris Agreement is an international treaty on climate change adopted by 196 Parties at the UN Climate Change Conference (COP21) in Paris, France, on 12

December 2015. It entered into force on 4 November 2016. Its goal is to hold "the increase in the global average temperature to well below 2°C above pre-industrial levels" and pursue efforts "to limit the temperature increase to 1.5°C above pre-industrial levels." It does this primarily by allowing parties to set their own Nationally Determined Contributions (NDCs) to climate mitigation.

Self-perpetuating feedbacks Also referred to as *self-reinforcing feedbacks* or *self-sustaining feedbacks*. A type of amplifying (positive) feedback in which an initial change to a system generates a response that 1) reinforces the change and 2) is equal to or greater than the initial change. If this happens, the feedback loop perpetuates itself in a vicious cycle.

Tipping point A critical threshold beyond which a system reorganizes or switches states, sometimes abruptly and/or irreversibly.

References

[1] Xu Y. & Ramanathan V. (2017) *Well below 2 °C: Mitigation strategies for avoiding dangerous to catastrophic climate changes*, PROC. NAT'L. ACAD. SCI. 114(39): 10315–10323, 10321 ("Constrained by CO_2 lifetime and the diffusion time of new technologies (decades), the scenarios considered here (SI Appendix, Fig. S2A) suggest that about half of the 2.6 °C CO_2 warming in the baseline-fast scenario can be mitigated by 2100 and only 0.1–0.3 °C can be mitigated by 2050… The SP [super pollutant] lever targets SLCPs. Reducing SLCP emissions thins the SP blanket within few decades, given the shorter lifetimes of SLCPs (weeks for BC to about 15 years for HFCs). The mitigation potential of the SP lever with a maximum deployment of current technologies … is about 0.6 °C by 2050 and 1.2 °C by 2100 (SI Appendix, Fig. S5B and Table S1)."). *See also* Climate & Clean Air Coalition, *Short-Lived Climate Pollutants* (*last visited* 24 February 2025) ("Maximum possible reductions in short-lived climate pollutants – which can achieve a 0.6°C reduction in warming – must be combined with maximum possible CO_2 reductions to slow the rate of global warming and achieving the 1.5°C target set by the Paris Agreement."). Note that this does not include the impacts of unmasked warming as cooling sulfate aerosols, co-emitted when fossil fuels are burned, quickly decline under decarbonization policies.

[2] Dreyfus G. B., Xu Y., Shindell D. T., Zaelke D., & Ramanathan V. (2022) *Mitigating climate disruption in time: A self-consistent approach for avoiding both near-term and long-term global warming*, PROC. NAT'L. ACAD. SCI. 119(22): 1–8, 5 ("By 2050, the net avoided warming from the targeted non-CO_2 measures is 0.26°C, almost 4 times larger than the net benefit of decarbonization alone (0.07°C) (Table S5).").

[3] Dreyfus G. B., Xu Y., Shindell D. T., Zaelke D., & Ramanathan V. (2022) *Mitigating climate disruption in time: A self-consistent approach for avoiding both near-term and long-term global warming*, PROC. NAT'L. ACAD. SCI. 119(22): 1–8, 1, 5 ("We find that mitigation measures that target only decarbonization are essential for strong long-term cooling but can result in weak near-term warming (due to unmasking the cooling effect of co-emitted aerosols) and lead to temperatures exceeding 2°C before 2050. In contrast, pairing decarbonization with additional mitigation measures targeting short-lived climate pollutants (SLCPs) and N_2O, slows the rate of warming a decade or two earlier than decarbonization alone and avoids the 2°C threshold altogether. These non-CO_2 targeted measures when combined with decarbonization can provide net cooling by 2030, reduce the rate of warming from 2030 to 2050 by about 50%, roughly half of which comes from methane, significantly larger than decarbonization alone over this timeframe. … Aggressive decarbonization to achieve net-zero CO_2 emissions in the 2050s (as in the decarb-only scenario) results in weakly accelerated net warming compared to the reference case, with a positive warming up to 0.03 °C in the mid-2030s, and no net avoided warming until the mid-2040s due to the reduction in co-emitted cooling aerosols (Figure 3a). By 2050, decarbonization measures result in very limited net avoided warming (0.07°C), consistent with Shindell and Smith, but rise to a likely detectable 0.25°C by 2060 and a major benefit of 1.4°C by 2100 (Table S5). In contrast, pairing decarbonization with mitigation measures targeting CH_4, BC, HFC, and N_2O (not an SLCP due to its longer lifetime) independent from decarbonization are essential to slowing the rate of warming by the 2030s to under 0.3°C per decade (Table 1, Figure 3b), similar to the 0.2°C to 0.25°C per decade warming prior to 2020. Recent studies suggest that rate of warming rather than level of warming controls likelihood of record-shattering extreme weather events. By 2050, the net avoided warming from the targeted non-CO_2 measures is 0.26°C, almost 4 times larger than the net benefit of decarbonization alone (0.07°C) (Table S5).").

[4] United Nations Environment Programme & World Meteorological Organization (2011) INTEGRATED ASSESSMENT OF BLACK CARBON AND TROPOSPHERIC OZONE, 254, 262 ("Evaluating global mean temperature change, it was found that the targeted measures to reduce emissions of methane and BC [black carbon] could greatly reduce warming rates over the next few decades (Figure 6.1; Box 6.1). When all measures are fully implemented, warming during the 2030s relative to the present would be only half as much as in the reference scenario. In contrast, even a fairly aggressive strategy to reduce CO_2 emissions, as for the CO_2-measures scenario, does little to mitigate warming until after the next 20-30 years (Box 6.2) … Large impacts of the measures examined here were also seen for the Arctic despite the minimal amount of emissions currently taking place there. This occurs due to the high sensitivity of the Arctic both to pollutants that are transported there from remote sources and to radiative forcing that takes place in areas of the northern hemisphere outside the Arctic. The 16 measures examined here, including the measures on pellet stoves and coal briquettes, reduce warming in the Arctic by 0.7 ºC (range 0.2 to 1.3 ºC) at 2040. This is a large portion of the 1.1 ºC (range 0.7 to 1.7 ºC) warming projected under the reference scenario for the Arctic, and hence implementation of

the measures would be virtually certain to substantially slow, but not halt, the pace of Arctic climate change."). *See also* Shindell D., et al. (2012) *Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security*, SCIENCE 335(6065): 183–189, 184–185 ("The global mean response to the CH_4 plus BC measures was –0.54 ± 0.05ºC in the climate model. … Roughly half the forcing is relatively evenly distributed (from the CH_4 measures). The other half is highly inhomogeneous, especially the strong BC forcing, which is greatest over bright desert and snow or ice surfaces. Those areas often exhibit the largest warming mitigation, making the regional temperature response to aerosols and ozone quite distinct from the more homogeneous response to well-mixed greenhouse gases…. BC albedo and direct forcings are large in the Himalayas, where there is an especially pronounced response in the Karakoram, and in the Arctic, where the measures reduce projected warming over the next three decades by approximately two thirds and where regional temperature response patterns correspond fairly closely to albedo forcing (for example, they are larger over the Canadian archipelago than the interior and larger over Russia than Scandinavia or the North Atlantic)."); *and* Szopa S., Naik V., Adhikary B., Artaxo P., Berntsen T., Collins W. D., Fuzzi S., Gallardo L., Kiendler-Scharr A., Klimont Z., Liao H., Unger N., & Zanis P. (2021) *Chapter 6: Short-lived climate forcers*, in CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Masson-Delmotte V., et al. (eds.), 821 ("Across the SSPs, the collective reduction of CH_4, ozone precursors and HFCs can make a difference of global mean surface air temperature of 0.2 with a very likely range of [0.1–0.4] °C in 2040 and 0.8 with a very likely range of [0.5–1.3] °C at the end of the 21st century (comparing SSP3-7.0 and SSP1-1.9), which is substantial in the context of the Paris Agreement. Sustained methane mitigation, wherever it occurs, stands out as an option that combines near- and long-term gains on surface temperature (high confidence) and leads to air quality benefits by reducing surface ozone levels globally (high confidence).").

[5] Ripple W. J., Wolf C., Gregg J. W., Rockström J., Mann M. E., Oreskes N., Lenton T. M., Rahmstorf S., Newsome T. M., Xu C., Svenning J.-C., Pereira C. C., Law B. E., & Crowther T. W. (2024) *The 2024 state of the climate report: Perilous times on planet Earth*, BIOSCI.: 1–13, 1 ("Five of sixteen climate tipping elements are likely to cross their tipping points at 1.5°C: the Greenland ice sheet, the West Antarctic ice sheet, boreal permafrost, low-latitude coral reefs, and the Barents Sea Ice (Armstrong McKay et al. 2022).").

[6] Diffenbaugh N. S. & Barnes E. A. (2023) *Data-driven predictions of the time remaining until critical global warming thresholds are reached*, PROC. NAT'L. ACAD. SCI. 120(6): 1–9, 2 ("For 1.5 °C, the observed pattern of annual temperature anomalies in 2021 leads to a predicted time-to-threshold of 2035 (2030 to 2040) in the High scenario, 2033 (2028 to 2039) in the Intermediate scenario, and 2033 (2026 to 2041) in the Low scenario (Fig. 3). For 2 °C, the observed pattern of annual temperature anomalies in 2021 leads to a predicted time-to-threshold of 2050 (2043 to 2058) in the High scenario, 2049 (2043 to 2055) in the Intermediate scenario, and 2054 (2044 to 2065) in the Low scenario."). *See also* Friedlingstein P., *et al.* (2025) *Global Carbon Budget 2024*, EARTH SYST. SCI. DATA 17(3): 965–1039, 969 ("The remaining carbon budget for a 50 % likelihood to limit global warming to 1.5, 1.7, and 2 °C above the 1850–1900 level has been reduced to 65 GtC (235 $GtCO_2$), 160 GtC (585 $GtCO_2$), and 305 GtC (1110 $GtCO_2$), respectively, from the beginning of 2025, equivalent to around 6, 14, and 27 years, assuming 2024 emissions levels."); Hausfather Z. (13 June 2024) *Analysis: What record global heat means for breaching the 1.5C warming limit*, CARBON BRIEF ("There is no single best way to assess when the world will likely pass 1.5C. But both Carbon Brief's approach and those of other groups all agree it will most likely happen in the late 2020s or early 2030s in a world (SSP2-4.5) where global emissions remain around current levels."); *and* Hansen J. E., *et al.* (2025) *Global Warming Has Accelerated: Are the United Nations and the Public Well-Informed?*, ENVIRON. SCI. POLICY SUSTAIN. DEV. 67(1): 6–44, 35 ("A declining solar irradiance may dampen warming for several years, but global warming in the next two decades is likely to be about 0.2-0.3 °C per decade, leading to global temperature +2 °C by 2045.").

[7] Ramanathan V., Suárez-Orozco M., von Braun J., Alford H., Turkson P., Gustafsson O., Hassan M., Schellnhuber J., Viana V., Lee H., McCarthy G., Narain S., Dryefus G., Farrar J., Kimutai J., Hoffer M., Suárez-Orozco C., Swaminathan S., Picolotti R., & Yu K. (2024) *Planetary Call to Action for Climate Change Resilience*, Pontifical Academy of Sciences & Pontifical Academy of Social Sciences, 4 ("Doing everything in our power to rapidly reduce global greenhouse gas emissions and bend the warming curve by 2050 to limit temporary overshoot to below 2ºC and to limit the warming to 1.5ºC as soon as possible, is the first pillar of MAST …[The three MAST pillars are: Mitigation to reduce climate risks; Adaptation to manage unavoidable risks; and Societal Transformation to enable mitigation

and adaptation] and also prioritizing nature-based solutions in the proactive removal of CO_2 from the atmosphere. We must drastically reduce four short-lived climate pollutants (methane, black carbon soot, tropospheric ozone, and HFCs) to reduce the rate of warming by half in the short term (<25 years). We need massive acceleration of the global decarbonization process by transitioning away from fossil fuels during the same time."). *See also* Ramanathan V. & von Braun J. (Eds.) (2023) *Resilience of People and Ecosystems under Climate Stress*, Proceedings of a Conference, Casina Pio IV, Vatican City, 13-14 July 2022, Libreria Editrice Vaticana: Vatican City, 20 ("Climate resilience needs to be built on three pillars: First Pillar – Mitigation to reduce climate change risks; Second Pillar – Adaptation to reduce exposure and vulnerability to climate changes that are unavoidable; and Third Pillar – Transformation of society to develop the capacity to prepare and plan for mitigation and adaptation. This transformation needs to happen bottom-up from the level of an individual and a community to national level."); *and* von Braun J., Ramanathan V., & Turkson P. K. A. (2022) *Resilience of people and ecosystems under climate stress*, Pontifical Academy of Sciences, 6 ("Recommendations: Resilience building must rest on three pillars: Mitigation, Adaptation & Transformation. Mitigation: Reduce climate risks…. Adaptation: Reduce exposure and vulnerability to unavoidable climate risks. Exposure & vulnerability reduction has three faces: Reductions in sensitivity to climate change; Reductions in risk exposure; & enhancement of adaptative capacity. There are limits to adaptation and hence adaptation has to be integrated with mitigation actions to avoid crossing the limits."). The definition of resilience is taken from Möller V., van Diemen R., Matthews J. B. R., Méndez C., Semenov S., Fuglestvedt J. S., & Resinger A. (2022) Annex II: Glossary, in CLIMATE CHANGE 2022: IMPACTS, ADAPTATION, AND VULNERABILITY, *Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Pörtner H.-O., Roberts D. C., Tignor M., Poloczanska E. S., Mintenbeck K., Alegría A., Craig M., Langsdorf S., Löschke S., Möller V., Okem A., & Rama B. (eds.), 2920–2921 ("The capacity of interconnected social, economic and ecological systems to cope with a hazardous event, trend or disturbance, responding or reorganising in ways that maintain their essential function, identity and structure. Resilience is a positive attribute when it maintains capacity for adaptation, learning and/or transformation (Arctic Council, 2016).").

[8] Forster P. M., *et al.* (2024) *Indicators of Global Climate Change 2023: annual update of key indicators of the state of the climate system and human influence*, EARTH SYST. SCI. DATA 16(6): 2625–2658, 2643 ("Therefore, the rate of human-induced warming for the 2014–2023 decade is concluded to be 0.26 °C per decade with a range of [0.2–0.4] °C per decade)."). *See also* Rohde R. (10 January 2025) *Global Temperature Report for 2024*, Berkeley Earth ("Since 1980, the overall trend has been about +0.20 °C/decade (+0.36 °F/decade). The extreme warmth in 2023/2024 likely points to a period of greater warming. However, whether that greater warming rate persists over the long-term or is only present briefly is hard to predict. To the extent that excess recent warming is likely driven by reductions in man-made aerosol pollution, future warming from this source will also depend directly on human choices regarding the regulation of such aerosols."); *and* Samset B. H., Lund M. T., Fuglestvedt J. S., & Wilcox L. J. (2024) *2023 temperatures reflect steady global warming and internal sea surface temperature variability*, COMMUN. EARTH ENVIRON. 5(1): 1–8, 2 ("All support the conclusion that 2023 had a strong contribution to its temperature anomaly from the SST [sea surface temperature] pattern, but not an unprecedented one. … After Green's function-based filtering, we find warming rates (in HadCRUT5) for the recent 10 (2014–2023), 20 (2004–2023) and 50 (1974–2023) years of 0.29, 0.27, 0.19 °C/decade, respectively."). For discussion of higher rates of warming predicted by higher-than-expected climate sensitivity to GHGs and aerosols, *see* Hansen J. E., *et al.* (2025) *Global Warming Has Accelerated: Are the United Nations and the Public Well-Informed?*, ENVIRON. SCI. POLICY SUSTAIN. DEV. 67(1): 6–44, 35 ("A declining solar irradiance may dampen warming for several years, but global warming in the next two decades is likely to be about 0.2-0.3 °C per decade, leading to global temperature +2 °C by 2045."); *and* Hansen J. E., Sato M., Simons L., Nazarenko L. S., Sangha I., Kharecha P., Zachos J. C., von Schuckmann K., Loeb N. G., Osman M. B., Jin Q., Tselioudis G., Jeong E., Lacis A., Ruedy R., Russell G., Cao J., & Li J. (2023) *Global warming in the pipeline*, OXF. OPEN CLIM. CHANGE 3(1): 1–33, 21 ("With current policies, we expect climate forcing for a few decades post-2010 to increase 0.5–0.6 W/m^2 per decade and produce global warming of at least +0.27°C per decade." … Figure 25 caption reads "Edges of the predicted post-2010 accelerated warming rate (see text) are 0.36 and 0.27°C per decade."). For early predictions of accelerated warming, *see* Xu Y., Ramanathan V., & Victor D. G. (2018) *Global warming will happen faster than we think*, NATURE 564(7734): 30–32, 31 ("In 2017, industrial carbon dioxide emissions are estimated to have reached about 37 gigatonnes[2]. This puts them on track with the highest emissions trajectory the IPCC has modelled so far. This dark news means that the next 25 years are poised to warm at a rate of

0.25–0.32 °C per decade[3]. That is faster than the 0.2 °C per decade that we have experienced since the 2000s, and which the IPCC used in its special report.").

[9] Bustamante M., *et al.* (2023) *Ten New Insights in Climate Science 2023/2024*, GLOB. SUSTAIN.: 1–58, 43 ("Few pathways remain that avoid a 1.5°C overshoot; pathways with no or limited overshoot require emissions to peak before 2025 and be cut by 43% by 2030 relative to 2019 levels (IPCC, 2022b, Ch3 p. 329), representing a 6% decrease each year. Research since AR6 indicates overshooting 1.5°C is all but inevitable in the near term[.]"). *See also* Diffenbaugh N. S. & Barnes E. A. (2024) *Data-Driven Predictions of Peak Warming Under Rapid Decarbonization*, GEOPHYS. RES. LETT. 51(23): 1–10, 1 ("Predicting future warming under different cumulative emissions, we find that even if net-zero emissions are achieved mid-century, mean warming is virtually certain to exceed 1.5°C and has even odds of reaching 2°C, with high likelihood of individual years that are at least 0.5°C hotter than 2023."); Bevacqua E., Schleussner C.-F., & Zscheischler J. (2025) *A year above 1.5 °C signals that Earth is most probably within the 20-year period that will reach the Paris Agreement limit*, NAT. CLIM. CHANG.: 1–4, 2 ("On the basis of multiple observational datasets, climate model simulations and an idealized experiment, our analyses demonstrate that, unless ambitious emissions cuts are implemented, the world's first year at 1.5 °C warming is virtually certain (~99% on average; Fig. 1b) to fall within the 20-year period that reaches the 1.5 °C warming level."); *and* Hansen J. E., *et al.* (2025) *Global Warming Has Accelerated: Are the United Nations and the Public Well-Informed?*, ENVIRON. SCI. POLICY SUSTAIN. DEV. 67(1): 6–44, 24 ("Global warming of 0.2 °C from ship aerosol reduction will grow slowly beyond year 5 of forcing initiation (Figure 14), but it will prevent global temperature from falling much below +1.5 °C relative to preindustrial (late 19th century) time. Thus, our prediction is that global temperature averaged over the El Niño/ La Niña cycle has already reached the +1.5 °C threshold.").

[10] Copernicus Climate Change Service (10 January 2025) *Global Climate Highlights 2024* ("2024 was 0.72°C warmer than the 1991–2020 average, and 1.60°C warmer than the pre-industrial level, making it the first calendar year to exceed 1.5°C above that level."). Note that different international organizations measure the temperature anomaly against different pre-industrial datasets, leading to small variations between the temperatures reported by different agencies; for other estimates, *see* National Oceanic and Atmospheric Administration (10 January 2025) *2024 was the world's warmest year on record* ("In 2024, global temperature exceeded the pre-industrial (1850–1900) average by 2.63 degrees F (1.46 degrees C)."); Rohde R. (10 January 2025) *Global Temperature Report for 2024*, Berkeley Earth ("The global annual average for 2024 in our dataset is estimated as 1.62 ± 0.06 °C (2.91 ± 0.11 °F) above the average during the period 1850 to 1900, which is traditionally used a reference for the pre-industrial period."); World Meteorological Organization (10 January 2025) *WMO confirms 2024 as warmest year on record at about 1.55°C above pre-industrial level* ("The global average surface temperature was 1.55 °C (with a margin of uncertainty of ± 0.13 °C) above the 1850-1900 average, according to WMO's consolidated analysis of the six datasets."); *and* Madge G. (10 January 2025) *2024: record-breaking watershed year for global climate*, Met Office ("The global average temperature for 2024 was 1.53±0.08°C above the 1850-1900 global average, according to the HadCRUT5 temperature series, collated by the Met Office, the University of East Anglia and the National Centre for Atmospheric Science."). For additional data points from other international organizations tracking temperature, *see* Hausfather Z. (10 January 2025) State of the climate: 2024 sets a new record as the first year above 1.5C, CARBON BRIEF.

[11] Copernicus Climate Change Service (9 April 2025) *Second-warmest March globally, large wet and dry anomalies in Europe* ("The global average surface air temperature for March 2025 in the C3S' reanalysis dataset ERA5 was 14.06ºC, 0.65ºC above the 1991-2020 average for March and only 0.08ºC below the warmest March on record, in 2024. It was the 20th month in the last 21 months with a global average temperature of more than 1.5ºC above the pre-industrial level, according to ERA5 data.").

[12] Ripple W. J., Wolf C., Gregg J. W., Rockström J., Mann M. E., Oreskes N., Lenton T. M., Rahmstorf S., Newsome T. M., Xu C., Svenning J.-C., Pereira C. C., Law B. E., & Crowther T. W. (2024) *The 2024 state of the climate report: Perilous times on planet Earth*, BIOSCI.: 1–13, 1 ("Of the 35 planetary vital signs we track annually (figures 2 and 3), 25 are at record levels (supplemental table S1).").

[13] Richardson K., *et al.* (2023) *Earth beyond six of nine planetary boundaries*, SCI. ADV. 9(37): 1–16, 4 (*See* "Fig.1. Current status of control variables for all nine planetary boundaries. Six of the nine boundaries are transgressed"

showing the transgressed boundaries as biogeochemical flows, freshwater change, land system change, biosphere integrity, climate change (as CO_2 concentration and radiative forcing), and novel entities. The remaining three non-transgressed boundaries are stratospheric ozone depletion, atmospheric aerosol loading, and ocean acidification.”).

[14] Intergovernmental Panel on Climate Change (2021) *Summary for Policymakers*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 15 (“With every additional increment of global warming, changes in extremes continue to become larger. For example, every additional 0.5°C of global warming causes clearly discernible increases in the intensity and frequency of hot extremes, including heatwaves (*very likely*), and heavy precipitation (*high confidence*), as well as agricultural and ecological droughts in some regions (*high confidence*). Discernible changes in intensity and frequency of meteorological droughts, with more regions showing increases than decreases, are seen in some regions for every additional 0.5°C of global warming (*medium confidence*). Increases in frequency and intensity of hydrological droughts become larger with increasing global warming in some regions (*medium confidence*). There will be an increasing occurrence of some extreme events unprecedented in the observational record with additional global warming, even at 1.5°C of global warming. Projected percentage changes in frequency are higher for rarer events (*high confidence*).”).

[15] The probability of “record-shattering” extreme climate events increases with the rate of near-term warming, while the frequency and intensity of extreme events scale with warming levels. *See* Fischer E. M., Sippel S., & Knutti R. (2021) *Increasing probability of record-shattering climate extremes*, NAT. CLIM. CHANGE 11: 689–685, Supplementary Information (“In the main manuscript, we illustrate a fundamental difference in the behavior of (i) the statistically expected return levels or return periods of extremes traditionally defined as anomalies relative to a reference period, i.e. the probability of exceeding a fixed threshold and (ii) the expected probability of record-shattering extremes. For (i) the statistically expected return periods and levels are largely proportional to the warming level independent of the emission pathway (RCP/SSP), whereas for (ii) the statistically expected probability differs for the same warming level depending on the warming rate of the underlying forced response (i.e. the multi-member mean warming) and thereby on the emission pathway (RCP or SSP).”); 689 [in main text] (“Here, we show models project not only more intense extremes but also events that break previous records by much larger margins. These record-shattering extremes, nearly impossible in the absence of warming, are likely to occur in the coming decades. We demonstrate that their probability of occurrence depends on warming rate, rather than global warming level, and is thus pathway-dependent. In high-emission scenarios, week-long heat extremes that break records by three or more standard deviations are two to seven times more probable in 2021–2050 and three to 21 times more probable in 2051–2080, compared to the last three decades.”).

[16] Friedlingstein P., *et al.* (2025) *Global Carbon Budget 2024*, EARTH SYST. SCI. DATA 17(3): 965–1039, 994 (“Current CO_2 concentrations in the atmosphere are unprecedented for the last 2 million years, and the current rate of atmospheric CO_2 increase is at least 10 times faster than at any other time during the last 800 000 years (Canadell et al., 2021).”).

[17] Friedlingstein P., *et al.* (2025) *Global Carbon Budget 2024*, EARTH SYST. SCI. DATA 17(3): 965–1039, 996, 1000 (“The effect of climate change [on oceans] is much weaker, reducing the ocean sink globally by 0.17 ± 0.05 GtC yr^{-1} (−5.9 % of S_{OCEAN}) during 2014–2023 (all models simulate a weakening of the ocean sink by climate change, range −3.4 % to −10.7 %).”; “Over the historical period, the land sink increased in pace with the anthropogenic emissions exponential increase (Fig. 3). … The negative effect of climate can be seen across the globe and is particularly strong in most of South America, Central America, the southwestern USA, central Europe, the western Sahel, southern Africa, Southeast Asia and southern China, and eastern Australia (Fig. 12b). Globally, over the 2014–2023 period, climate change reduces the land sink by 0.87 ± 0.56 GtC yr^{-1} (27 % of S_{LAND}).”). For more information on the land sink, *see* Ke P., *et al.* (2024) *Low latency carbon budget analysis reveals a large decline of the land carbon sink in 2023*, NATL. SCI. REV.: 1–35, 5 (“The net land CO_2 flux, including land use change emissions, decreased to reach a low value of 0.44 ± 0.21 GtC yr^{-1} in 2023, compared to an average of 2.04 GtC yr^{-1} in the period 2010-2022, based on the bottom-up models. This is a record low value compared to previous years since 2003, both in our models (Fig. 1b) and in the models used by the global budget[2]. The OCO-2 inversion diagnosed a small sink of 0.73 ± 0.30 GtC yr^{-1} for the starting El Nino similar to the previous El Niño of 2015-2016 which was nevertheless more extreme than the

moderate El Niño starting in June 2023. We will need to acquire fluxes until early 2024 to cover the entire period of the current El Niño and compare it to the 2015-2016 event."); *and* Pan Y., *et al.* (2024) *The enduring world forest carbon sink*, NATURE 631(8021): 563–569, 566 ("The regrowth carbon sink increased greatly in the 2000s and 2010s with expanded areas (Extended Data Table 1). Overall, the increasing tropical regrowth-forest carbon sink balanced the declining sink in intact forests across 1990 to 2020, resulting in a nearly constant tropical-forest carbon sink of around 2.5 ± 0.4 Pg C yr^{-1} for three decades (Table 1). Although the carbon sinks in tropical intact and regrowth forests were large, high emissions resulting from deforestation and degradation counteracted nearly all of these remarkable sinks, making tropical forest lands almost carbon neutral (Extended Data Fig. 3), with a small net sink or source of between −0.1 and 0.6 Pg C yr^{-1}, fluctuating with deforestation intensities in different decades (Table 1). … In the tropics there has been a shift from equal contributions of intact and regrowth tropical forests in the 1990s to 65% of the sink being in regrowth forests in the 2010s, as the intact sink declined and the regrowth sink increased (Table 1)."). For more information on the ocean sink, *see* Müller J. D., Gruber N., Carter B., Feely R., Ishii M., Lange N., Lauvset S. K., Murata A., Olsen A., Pérez F. F., Sabine C., Tanhua T., Wanninkhof R., & Zhu D. (2023) *Decadal Trends in the Oceanic Storage of Anthropogenic Carbon From 1994 to 2014*, AGU ADVANCES 4(4): 1–28, 18 ("For the global sensitivity β, we compute values of 1.6 ± 0.1 Pg C ppm^{-1} and 1.3 ± 0.1 Pg C ppm^{-1} for the two decades, respectively (Table 1, Figure 7). Their average confirms the long-term mean value of 1.4 ± 0.1 Pg C ppm^{-1} diagnosed by Gruber et al. (2023), but the significant decrease of about 15 ± 11% between the two decades indicates a weakening of the ocean sink for Cant. The reason that this difference in β is significant, while the 7 ± 12% reduction (−1.9 ± 3.6 Pg C dec^{-1}) in the global ΔC_{ant} [change in ocean CO_2 storage] inventory is not, is due to the ∼10% higher growth rate in atmospheric CO_2 from 2004 to 2014 compared to that during the previous decade (Table 1).").

[18] Canadell J. G., *et al.* (2021) *Chapter 5: Global Carbon and other Biogeochemical Cycles and Feedbacks*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), FAQ 5.1, 771 ("For decades, about half of the carbon dioxide (CO_2) that human activities have emitted to the atmosphere has been taken up by natural carbon sinks in vegetation, soils and oceans. These natural sinks of CO_2 have thus roughly halved the rate at which atmospheric CO_2 concentrations have increased, and therefore slowed down global warming. However, observations show that the processes underlying this uptake are beginning to respond to increasing CO_2 in the atmosphere and climate change in a way that will weaken nature's capacity to take up CO_2 in the future.").

[19] von Schuckmann K., *et al.* (2023) *Heat stored in the Earth system 1960–2020: where does the energy go?*, EARTH SYST. SCI. DATA 15(4): 1675–1709, 1694 ("In IPCC AR6, the total heat rate has been assessed by 0.57 (0.43 to 0.72) W m^{-2} for the period 1971–2018 and 0.79 (0.52 to 1.06) W m^{-2} for the period 2006–2018 (Forster et al., 2021). Consistently, we further infer a total heating rate of 0.76 ± 0.2 W m^{-2} for the most recent era (2006–2020). Thus, the rate of heat accumulation across the Earth system has increased during the most recent era as compared to the long-term estimate – an outcome which reconfirms the earlier finding in von Schuckmann et al. (2020) and which had then been concurrently and independently confirmed in Foster et al. (2021), Hakuba et al. (2021), Loeb et al. (2021), Liu et al. (2020), Raghuraman et al. (2021), and Kramer et al. (2021). The drivers of a larger EEI [Earth energy imbalance] in the 2000s than in the long-term period since 1971 are still unclear, and several mechanisms are discussed in literature. For example, Loeb et al. (2021) argue for a decreased reflection of energy back into space by clouds (including aerosol cloud interactions) and sea ice and increases in well-mixed greenhouse gases (GHG) and water vapor to account for this increase in EEI. Kramer et al. (2021) refer to a combination of rising concentrations of well-mixed GHG and recent reductions in aerosol emissions to be accounting for the increase, and Liu et al. (2020) address changes in surface heat flux together with planetary heat redistribution and changes in ocean heat storage.").

[20] Loeb N. G., Johnson G. C., Thorsen T. J., Lyman J. M., Rose F. G., & Kato S. (2021) *Satellite and Ocean Data Reveal Marked Increase in Earth's Heating Rate*, GEOPHYS. RES. LETT. 48(13): 1–8, 1 ("Marked decreases in clouds and sea-ice and increases in trace gases and water vapor combine to increase the rate of planetary heat uptake."). *See also* Goessling H. F., Rackow T., & Jung T. (2024) *Recent global temperature surge intensified by record-low planetary albedo*, SCIENCE 387(6729): 1–11, 1 ("In 2023, the global mean temperature soared to almost 1.5K above the pre-industrial level, surpassing the previous record by about 0.17K. Previous best-guess estimates of known drivers including anthropogenic warming and the El Niño onset fall short by about 0.2K in explaining the temperature rise. Utilizing satellite and reanalysis data, we identify a record-low planetary albedo as the primary factor bridging this

gap. The decline is apparently caused largely by a reduced low-cloud cover in the northern mid-latitudes and tropics, in continuation of a multi-annual trend. Further exploring the low-cloud trend and understanding how much of it is due to internal variability, reduced aerosol concentrations, or a possibly emerging low-cloud feedback will be crucial for assessing the current and expected future warming.").

[21] Forster P. M., et al. (2023) *Indicators of Global Climate Change 2022: annual update of large-scale indicators of the state of the climate system and human influence*, EARTH SYST. SCI. DATA 15(6): 2295–2327, 2308, 2309 ("Human-induced warming, also known as anthropogenic warming, refers to the component of observed global surface temperature increase over a specific period (for instance, from 1850–1900 as a proxy for pre-industrial climate to the last decade) attributable to both the direct and indirect effects of human activities, which are typically grouped as follows: well-mixed greenhouse gases (consisting of CO_2, CH_4, N_2O and F-gases) and other human forcings (consisting of aerosol–radiation interaction, aerosol–cloud interaction, black carbon on snow, contrails, ozone, stratospheric H_2O and land use) (Eyring et al., 2021). While total warming, the actual observed temperature change potentially resulting from both natural climate variability (internal variability of the climate system and the climate response to natural forcing) and human influences, is the quantity directly related to climate impacts and therefore relevant for adaptation, mitigation efforts focus on human-induced warming as the more relevant indicator for tracking progress against climate stabilisation targets. Further, as the attribution analysis allows human-induced warming to be disentangled from possible contributions from solar and volcanic forcing and internal variability (e.g. related to El Niño/La Nina events), it avoids misperception about short-term fluctuations in temperature. … AR6 defined the current human-induced warming relative to the 1850–1900 baseline as the decade average of the previous 10-year period (see AR6 WGI Chap. 3). This paper provides an update of the 2010–2019 period used in the AR6 to the 2013–2022 decade. SR1.5 defined current human-induced warming as the average of a 30-year period centred on the current year, assuming the recent rate of warming continues (see SR1.5 Chap. 1). This definition is currently almost identical to the present-day single-year value of human-induced warming, differing by about 0.01 ◦C (see results in Sect. 7.4); the attribution assessment in SR1.5 was therefore provided as a single-year warming."); 2297 ("In AR6 WGI and here, reaching a level of global warming is defined as the global surface temperature change, averaged over a 20-year period, exceeding a particular level of global warming, for example, 1.5 ◦C global warming. Given the current rates of change and the likelihood of reaching 1.5 ◦C of global warming in the first half of the 2030s (Lee et al., 2021, 2023; Riahi et al., 2022), it is important to have robust, trusted and also timely climate indicators in the public domain to form an evidence base for effective science-based decision-making."). However, the averaging periods and definitions used vary, with many meteorological services not differentiating the human-induced component from total warming. See for example Copernicus Climate Services, *Global Temperature Trends Monitor*, (last visited 18 August 2023) (""Global warming" at a point in time refers to the increase in a 30-year average, centred on the specified time, of Earth's global surface temperature relative to the pre-industrial period[.]").

[22] Arias P. A., *et al.* (2021) *Technical Summary*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 42 ("Timing of crossing 1.5°C global warming: Slightly different approaches are used in SR1.5 and in this Report. SR1.5 assessed a likely range of 2030 to 2052 for reaching a global warming level of 1.5°C (for a 30-year period), assuming a continued, constant rate of warming. In AR6, combining the larger estimate of global warming to date and the assessed climate response to all considered scenarios, the central estimate of crossing 1.5°C of global warming (for a 20-year period) occurs in the early 2030s, ten years earlier than the midpoint of the likely range assessed in the SR1.5, assuming no major volcanic eruption. (TS.1.3, Cross-Section Box TS.1)". *See also* Lee J.-Y., Marotzke J., Bala G., Cao L., Corti S., Dunne J. P., Engelbrecht F., Fischer E., Fyfe J. C., Jones C., Maycock A., Mutemi J., Ndiaye O., Panickal S., & T. Zhou (2021) *Chapter 4: Future Global Climate: Scenario-Based Projections and Near-Term Information*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 555 ("The threshold-crossing time is defined as the midpoint of the first 20-year period during which the average GSAT exceeds the threshold. In all scenarios assessed here except SSP5-8.5, the central estimate of crossing the 1.5°C threshold lies in the early 2030s. This is in the early part of the *likely* range (2030–2052) assessed in the IPCC Special Report on Global Warming of 1.5°C (SR1.5), which assumed continuation of the then-current warming rate; this rate has been confirmed in the AR6. Roughly half of this difference between assessed crossing times arises from a larger historical warming diagnosed in AR6. The other half arises because for central

estimates of climate sensitivity, *most scenarios show stronger warming over the near term than was assessed as 'current' in SR1.5* (*medium confidence*).”). Emphasis added.

[23] Diffenbaugh N. S. & Barnes E. A. (2023) *Data-driven predictions of the time remaining until critical global warming thresholds are reached*, PROC. NAT'L. ACAD. SCI. 120(6): 1–9, 2 (“For 1.5 °C, the observed pattern of annual temperature anomalies in 2021 leads to a predicted time-to-threshold of 2035 (2030 to 2040) in the High scenario, 2033 (2028 to 2039) in the Intermediate scenario, and 2033 (2026 to 2041) in the Low scenario (Fig. 3). For 2 °C, the observed pattern of annual temperature anomalies in 2021 leads to a predicted time-to-threshold of 2050 (2043 to 2058) in the High scenario, 2049 (2043 to 2055) in the Intermediate scenario, and 2054 (2044 to 2065) in the Low scenario.”), *discussed in* Harvey C. (31 January 2023) *AI Predicts Warming Will Surpass 1.5 C in a Decade*, SCIENTIFIC AMERICAN. *See also* Hausfather Z. (13 June 2024) *Analysis: What record global heat means for breaching the 1.5C warming limit*, CARBON BRIEF (“There is no single best way to assess when the world will likely pass 1.5C. But both Carbon Brief's approach and those of other groups all agree it will most likely happen in the late 2020s or early 2030s in a world (SSP2-4.5) where global emissions remain around current levels.”); *and* Hansen J. E., *et al.* (2025) *Global Warming Has Accelerated: Are the United Nations and the Public Well-Informed?*, ENVIRON. SCI. POLICY SUSTAIN. DEV. 67(1): 6–44, 35 (“A declining solar irradiance may dampen warming for several years, but global warming in the next two decades is likely to be about 0.2-0.3 °C per decade, leading to global temperature +2 °C by 2045.”).

[24] Betts R. A., Belcher S. E., Hermanson L., Klein Tank A., Lowe J. A., Jones C. D., Morice C. P., Rayner N. A., Scaife A. A., & Stott P. A. (2023) *Approaching 1.5 °C: how will we know we've reached this crucial warming mark?*, NATURE 624(7990): 33–35, 34 (“The year of exceedance of a GWL [global warming level] is the midpoint of the 20-year period at that level. By this definition, 1.5 °C of warming would be confirmed once the observed temperature rise has reached that level, on average, over a 20-year period — in other words, a decade after crossing the 1.5 °C level. … Assuming the world stays on its current warming trajectory, IPCC projections suggest that 1.5 °C will be breached around 2030, give or take a decade[3]. But, on the basis of 20-year averages, the passing of 1.5 °C would not be formally recognized until around 2040.”).

[25] Erdenesanaa D. (2 November 2023) *35 Years After Addressing Congress, James Hansen Has More Climate Warnings*, THE NEW YORK TIMES (““The 1.5 degree limit is deader than a doornail,” said Dr. Hansen, now the director of the Climate Science, Awareness and Solutions Program at Columbia University, during a news conference on Thursday. The 2 degrees goal could still be met, he said, but only with concerted action to stop using fossil fuels and at a pace far quicker than current plans.”).

[26] Hansen J. E., *et al.* (2025) *Global Warming Has Accelerated: Are the United Nations and the Public Well-Informed?*, ENVIRON. SCI. POLICY SUSTAIN. DEV. 67(1): 6–44, 29 (“The gravity of the situation is shown by Figure 15, which compares reality with the greenhouse gas scenario (RCP2.6) designed by IPCC to limit global warming to less than +2 °C. Annual growth of greenhouse climate forcing is now more than double the amount in IPCC's target scenario, which was never realistic because it relied on an assumption of massive carbon capture at powerplants with permanent burial of the captured CO_2.”); 35 (“Continued high temperature will support our ship aerosol forcing estimate of 0.5 W/m^2. Sea surface temperature will remain abnormally high, providing fuel for powerful storms and extreme rainfall. The 12-month running mean global temperature[150] (Figure 1) is the single most informative temperature diagnostic, but zonal-mean sea surface temperature (Figure 10) is pregnant with more information that helps us interpret climate change. A declining solar irradiance may dampen warming for several years, but global warming in the next two decades is likely to be about 0.2-0.3 °C per decade, leading to global temperature +2 °C by 2045. … The projected warming rate could slow if the growth rate of greenhouse gases slowed, but there is no evidence of that.”), *discussed in* Carrington D. (4 February 2025), Climate change target of 2C is 'dead', says renowned climate scientist, THE GUARDIAN (““The Intergovernmental Panel on Climate Change (IPPC) defined a scenario which gives a 50% chance to keep warming under 2C – that scenario is now impossible,” [Hansen] said. “The 2C target is dead, because the global energy use is rising, and it will continue to rise.””).

[27] Forster P. M., *et al.* (2024) *Indicators of Global Climate Change 2023: annual update of key indicators of the state of the climate system and human influence*, EARTH SYST. SCI. DATA 16(6): 2625–2658, 2643 (“Therefore, the rate of

human-induced warming for the 2014–2023 decade is concluded to be 0.26 °C per decade with a range of [0.2–0.4] °C per decade)."). *See also* Rohde R. (10 January 2025) *Global Temperature Report for 2024*, Berkeley Earth ("Since 1980, the overall trend has been about +0.20 °C/decade (+0.36 °F/decade). The extreme warmth in 2023/2024 likely points to a period of greater warming. However, whether that greater warming rate persists over the long-term or is only present briefly is hard to predict. To the extent that excess recent warming is likely driven by reductions in man-made aerosol pollution, future warming from this source will also depend directly on human choices regarding the regulation of such aerosols."); *and* Samset B. H., Lund M. T., Fuglestvedt J. S., & Wilcox L. J. (2024) *2023 temperatures reflect steady global warming and internal sea surface temperature variability*, COMMUN. EARTH ENVIRON. 5(1): 1–8, 2 ("All support the conclusion that 2023 had a strong contribution to its temperature anomaly from the SST [sea surface temperature] pattern, but not an unprecedented one. … After Green's function-based filtering, we find warming rates (in HadCRUT5) for the recent 10 (2014–2023), 20 (2004–2023) and 50 (1974–2023) years of 0.29, 0.27, 0.19 °C/decade, respectively."). For discussion of higher rates of warming predicted by higher-than-expected climate sensitivity to GHGs and aerosols, *see* Hansen J. E., *et al.* (2025) *Global Warming Has Accelerated: Are the United Nations and the Public Well-Informed?*, ENVIRON. SCI. POLICY SUSTAIN. DEV. 67(1): 6–44, 35 ("A declining solar irradiance may dampen warming for several years, but global warming in the next two decades is likely to be about 0.2-0.3 °C per decade, leading to global temperature +2 °C by 2045."); *and* Hansen J. E., Sato M., Simons L., Nazarenko L. S., Sangha I., Kharecha P., Zachos J. C., von Schuckmann K., Loeb N. G., Osman M. B., Jin Q., Tselioudis G., Jeong E., Lacis A., Ruedy R., Russell G., Cao J., & Li J. (2023) *Global warming in the pipeline*, OXF. OPEN CLIM. CHANGE 3(1): 1–33, 21 ("With current policies, we expect climate forcing for a few decades post-2010 to increase 0.5–0.6 W/m^2 per decade and produce global warming of at least +0.27°C per decade." … Figure 25 caption reads "Edges of the predicted post-2010 accelerated warming rate (see text) are 0.36 and 0.27°C per decade."). For early predictions of accelerated warming, *see* Xu Y., Ramanathan V., & Victor D. G. (2018) *Global warming will happen faster than we think*, NATURE 564(7734): 30–32, 31 ("In 2017, industrial carbon dioxide emissions are estimated to have reached about 37 gigatonnes[2]. This puts them on track with the highest emissions trajectory the IPCC has modelled so far. This dark news means that the next 25 years are poised to warm at a rate of 0.25–0.32 °C per decade[3]. That is faster than the 0.2 °C per decade that we have experienced since the 2000s, and which the IPCC used in its special report.").

[28] Intergovernmental Panel on Climate Change (2023) AR6 SYNTHESIS REPORT: CLIMATE CHANGE 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 42 ("Risks associated with large-scale singular events or tipping points, such as ice sheet instability or ecosystem loss from tropical forests, transition to high risk between 1.5°C–2.5°C (*medium confidence*) and to very high risk between 2.5°C–4°C (*low confidence*). The response of biogeochemical cycles to anthropogenic perturbations can be abrupt at regional scales and irreversible on decadal to century time scales (*high confidence*). The probability of crossing uncertain regional thresholds increases with further warming (*high confidence*).").

[29] Intergovernmental Panel on Climate Change (2022) *Summary for Policymakers*, *in* CLIMATE CHANGE 2022: MITIGATION OF CLIMATE CHANGE, *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Shukla P. R., Skea J., Slade R., Al Khourdajie A., van Diemen R., McCollum D., Pathak M., Some S., Vyas P., Fradera R., Belkacemi M., Hasija A., Lisboa G., Luz S., & Malley J. (eds.), 23, 24 ("Deep GHG emissions reductions by 2030 and 2040, particularly reductions of methane emissions, lower peak warming, reduce the likelihood of overshooting warming limits and lead to less reliance on net negative CO_2 emissions that reverse warming in the latter half of the century… Future non-CO_2 warming depends on reductions in non-CO_2 GHG, aerosol and their precursor, and ozone precursor emissions. In modelled global low emission pathways, the projected reduction of cooling and warming aerosol emissions over time leads to net warming in the near- to mid-term. In these mitigation pathways, the projected reductions of cooling aerosols are mostly due to reduced fossil fuel combustion that was not equipped with effective air pollution controls. Non-CO_2 GHG emissions at the time of net zero CO_2 are projected to be of similar magnitude in modelled pathways that limit warming to 2°C (>67%) or lower. These non-CO_2 GHG emissions are about 8 [5–11] $GtCO_2$-eq per year, with the largest fraction from CH_4 (60% [55–80%]), followed by N_2O (30% [20–35%]) and F-gases (3% [2–20%]). [FOOTNOTE 52] Due to the short lifetime of CH_4 in the atmosphere, projected deep reduction of CH_4 emissions up until the time of net zero CO_2 in

modelled mitigation pathways effectively reduces peak global warming. (*high confidence*)"). *See also* Hansen J., Sato M., Ruedy R., & Simons L. (13 October 2023) *El Nino Fizzles. Planet Earth Sizzles. Why?*, Columbia University, 3 ("Much of the aerosol pollution arises from fossil fuels, so, as the world moves to clean energies, aerosol amounts should decline and unmask the GHG warming that had been compensated by aerosol cooling. (We long ago described this aerosol cooling as a Faustian bargain, and later discussed it in more detail.)"); Szopa S., Naik V., Adhikary B., Artaxo P., Berntsen T., Collins W. D., Fuzzi S., Gallardo L., Kiendler-Scharr A., Klimont Z., Liao H., Unger N., & Zanis P. (2021) *Chapter 6: Short-lived climate forcers*, in CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 822 ("Additional methane and BC mitigation would contribute to offsetting the additional warming associated with SO_2 reductions that would accompany decarbonization (*high confidence*)."); Ramanathan V. & Feng Y. (2008) *On avoiding dangerous anthropogenic interference with the climate system: Formidable challenges ahead*, PROC. NAT'L. ACAD. SCI. 105(38): 14245–14250, 14248 ("Switching from coal to ''cleaner'' natural gas will reduce CO_2 emission and thus would be effective in minimizing future increases in the committed warming. However, because it also reduces air pollution and thus the ABC [Atmospheric Brown Cloud] masking effect, it may speed up the approach to the committed warming of 2.4°C (1.4–4.3°C)."); United Nations Environment Programme & World Meteorological Organization (2011) INTEGRATED ASSESSMENT OF BLACK CARBON AND TROPOSPHERIC OZONE, 254 ("Evaluating global mean temperature change, it was found that the targeted measures to reduce emissions of methane and BC could greatly reduce warming rates over the next few decades (Figure 6.1; Box 6.1). When all measures are fully implemented, warming during the 2030s relative to the present would be only half as much as in the reference scenario. In contrast, even a fairly aggressive strategy to reduce CO_2 emissions, as for the CO_2-measures scenario, does little to mitigate warming until after the next 20-30 years (Box 6.2). In fact, sulphur dioxide (SO_2) is coemitted with CO_2 in some of the most highly emitting activities, coal burning in large-scale combustion such as in power plants, for example, that are obvious targets for reduced usage under a CO_2-emissions mitigation strategy. Hence such strategies can lead to additional near-term warming (Figure 6.1), in a well-known temporary effect (e.g. Raes and Seinfeld, 2009), although most of the near-term warming is driven by CO_2 emissions in the past. The CO_2-measures scenario clearly leads to long-term benefits however, with a dramatically lower warming rate at 2070 under that scenario than under the scenario with only CH_4 and BC measures (see Figure 6.1 and timescales in Box 6.2). Hence the near-term measures clearly cannot be substituted for measures to reduce emissions of long-lived GHGs. The near-term measures largely target different source sectors for emissions than the CO_2 measures, so that the emissions reductions of the short-lived pollutants are almost identical regardless of whether the CO_2 measures are implemented or not, as shown in Chapter 5. The near-term measures and the CO_2 measures also impact climate change over different timescales owing to the different lifetimes of these substances. In essence, the near-term CH_4 and BC measures are effectively uncoupled from CO_2 measures examined here.").

[30] International Energy Agency (2023) CREDIBLE PATHWAYS TO 1.5 °C - FOUR PILLARS FOR ACTION IN THE 2020S, 1–15, 3, 11 ("In the energy sector, decarbonising electricity, accelerating energy efficiency and electrification are the critical tools. Capacity additions of renewables need to triple from 2022 levels by 2030, reaching around 1200 GW annually, representing on average 90% of new generation capacity each year. Electric car sales should reach a market share of around 60% by 2030, while zero emissions medium and heavy freight trucks should reach a market share of around 35% by the same year. Reducing deforestation to net zero by 2030 – in line with The Glasgow Leaders' Declaration on Forests and Land Use – provides the largest share of CO_2 emissions reductions from the land-use sector. Tackling non-CO_2 emissions is vital to limiting peak warming. Assuming strong action on CO_2, meeting or exceeding commitments like the Kigali Amendment on HFCs and the Global Methane Pledge, and acting on non-CO_2 emissions from agriculture, could make the difference between a scenario which substantially overshoots 1.5 °C, risking triggering irreversible climate tipping points, and one which does not. Even in a low overshoot scenario, carbon capture and storage and atmospheric carbon dioxide removal will be required to mitigate and compensate hard-to-abate residual emissions. Projects capturing around 1.2 Gt CO_2 by 2030 need to be implemented, against the roughly 0.3 Gt CO_2 currently planned for 2030. A credible pathway to the 1.5 °C goal needs strong, immediate action on each of these four pillars, to deliver immediate and rapid emissions reductions; strong contributions from all countries, especially advanced and major economies; and clear policy signals to enable actors to anticipate and achieve change. … Methane is responsible for around 30% of the rise in global temperatures since the Industrial Revolution, and cutting methane emissions in the NZE Scenario has the single biggest impact after CO_2 on limiting the temperature rise to 2050. One hundred and fifty countries have now joined the Global Methane Pledge, which was launched at

COP26 in 2021 and aims to reduce methane emissions from human activity by at least 30% from 2020 levels by 2030. The energy sector accounts for around 40% of total methane emissions attributable to human activity, second only to agriculture. In the NZE Scenario, methane emissions from the energy sector fall by around 75% between 2020 and 2030 and total methane emissions from human activity fall by around 45%. The IEA's latest update of its Global Methane Tracker found that methane emissions from oil and gas alone could be reduced by 75% with existing technologies. Around $100 billion in total investment is needed over the period to 2030 to achieve this reduction—equivalent to less than 3% of oil and gas net income in 2022. To address methane emissions from fossil energy production and consumption, countries covering over half of global gas imports and over one-third of global gas exports released a Joint Declaration from Energy Importers and Exporters on Reducing Greenhouse Gas Emissions from Fossil Fuels at COP27 calling for minimizing flaring, methane, and CO_2 emissions across the supply chain to the fullest extent practicable.").

[31] Intergovernmental Panel on Climate Change (2022) *Summary for Policymakers*, *in* CLIMATE CHANGE 2022: MITIGATION OF CLIMATE CHANGE, *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Shukla P. R., Skea J., Slade R., Al Khourdajie A., van Diemen R., McCollum D., Pathak M., Some S., Vyas P., Fradera R., Belkacemi M., Hasija A., Lisboa G., Luz S., & Malley J. (eds.), SPM-22 ("In pathways that limit warming to 1.5°C (>50%) with no or limited overshoot global net CO_2 emissions are reduced compared to modelled 2019 emissions by 48% [36–69%] in 2030 and by 80% [61-109%] in 2040; and global CH_4 emissions are reduced by 34% [21–57%] in 2030 and 44% [31-63%] in 2040. … [FOOTNOTE 44] Across most modelled pathways, this is the maximum technical potential for anthropogenic CH_4 reductions in the underlying models (*high confidence*). Further emissions reductions, as illustrated by the IMP-SP pathway, may be achieved through changes in activity levels and/or technological innovations beyond those represented in the majority of the pathways (*medium confidence*). Higher emissions reductions of CH_4 could further reduce peak warming. (*high confidence*) (Figure SPM.5)").

[32] Intergovernmental Panel on Climate Change (2022) *Summary for Policymakers*, *in* CLIMATE CHANGE 2022: MITIGATION OF CLIMATE CHANGE, *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Shukla P. R., Skea J., Slade R., Al Khourdajie A., van Diemen R., McCollum D., Pathak M., Some S., Vyas P., Fradera R., Belkacemi M., Hasija A., Lisboa G., Luz S., & Malley J. (eds.), SPM-22 ("In pathways that limit warming to 1.5°C (>50%) with no or limited overshoot global net CO_2 emissions are reduced compared to modelled 2019 emissions by 48% [36–69%] in 2030 and by 80% [61-109%] in 2040[.]")

[33] Intergovernmental Panel on Climate Change (2022) *Summary for Policymakers*, *in* CLIMATE CHANGE 2022: MITIGATION OF CLIMATE CHANGE, *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Shukla P. R., Skea J., Slade R., Al Khourdajie A., van Diemen R., McCollum D., Pathak M., Some S., Vyas P., Fradera R., Belkacemi M., Hasija A., Lisboa G., Luz S., & Malley J. (eds.), SPM-22 ("C.1.2 In modelled pathways that limit warming to 2°C (>67%) assuming immediate action, global net CO_2 emissions are reduced compared to modelled 2019 emissions by 27% [11–46%] in 2030 and by 52% [36-70%] in 2040[.] … In pathways that limit warming to 1.5°C (>50%) with no or limited overshoot global net CO_2 emissions are reduced compared to modelled 2019 emissions by 48% [36–69%] in 2030 and by 80% [61-109%] in 2040; and global CH_4 emissions are reduced by 34% [21–57%] in 2030 and 44% [31-63%] in 2040. There are similar reductions of non-CO_2 emissions by 2050 in both types of pathways: CH_4 is reduced by 45% [25–70%]; N_2O is reduced by 20% [-5 – 55%]; and F-Gases are reduced by 85% [20–90%].").

[34] United Nations (2024) SURGING SEAS IN A WARMING WORLD, 9 ("Small rises in relative sea-level can disproportionately increase coastal flood frequency.[34] According to the United Nations Development Programme (UNDP) and the Climate Impact Lab (CIL), the extent of coastal flooding has increased over the past 20 years as a result of SLR, meaning 14 million more people worldwide now live in coastal communities with a 1-in-20-year chance of flooding.[35]").

[35] Islamic Relief (13 October 2022) *Pakistan monsoon floods 2022 Islamic Relief Pakistan* ("1,717 DEAD 33 Million PEOPLE AFFECTED 12,867 INJURED 436 BRIDGE DAMAGED 13,115 ROADS DAMAGED 2,114,546 HOUSES DAMAGED 1,163,635 LIVESTOCK PERISHED").

[36] Clarke B., Otto F., & Harrington L. (5 September 2022) *Pakistan floods: What role did climate change play?*, THE CONVERSATION ("Clues as to the role of climate change can also come from aspects that contributed to this disaster. There are three main factors. ¶ First, extreme rainfall. A warmer atmosphere holds more moisture. For every degree the atmosphere warms it can hold about 6%-7% more moisture, which often results in more rain falling during the most extreme events (south Asia has warmed around 0.7°C since 1900). Had this event happened in a world where carbon dioxide concentrations were instead at pre-industrial levels, the rains probably would have been less intense. ¶ Second, the monsoon itself, which is highly complex and variable. It forms in south Asia in the summer, when air over land warms faster than air over the sea, which creates a flow of air onto the land. The winds bring great volumes of moisture that precipitate into deluges when they meet higher ground, especially the Himalayas. ¶ Unusual monsoon rains over Pakistan have some predictability. They occur when multiple phenomena coincide, including a La Niña event in the Pacific and large meanders in the high-altitude jet stream, as was the case in both 2010 and this year. ¶ There is emerging evidence that this confluence of factors may occur more regularly as the climate changes. If such trends continue, then flooding in Pakistan and other simultaneous extremes across the northern Hemisphere will happen more often in the future. ¶ Pakistan also experienced extended and brutal heatwaves in May and June this year, which were amplified by climate change. This heat amplified the monsoonal "thermal low"—a low-pressure system created by hot air rising rapidly—which greatly enhanced the flow of moisture-laden air onto southern Pakistan. ¶ Third, Pakistan has more than 7,000 glaciers in its northern mountainous regions. As these glaciers melt, their waters contribute to the flooding. This melting is driven to a large degree by climate change and is especially prominent this year as a result of the heatwave."). *See also* Otto F. E. L., Zachariah M., Saeed F., Siddiqi A., & Shahzad K. (2022) *Climate change likely increased extreme monsoon rainfall, flooding highly vulnerable communities in Pakistan*, WORLD WEATHER ATTRIBUTION, 3 ("However, for the 5-day rainfall extreme, the majority of models and observations we have analysed show that intense rainfall has become heavier as Pakistan has warmed. Some of these models suggest climate change could have increased the rainfall intensity up to 50% for the 5-day event definition."); *and* Trenberth K. (15 September 2022) *2022's supercharged summer of climate extremes: How global warming and La Niña fueled disasters on top of disasters*, THE CONVERSATION.

[37] World Meteorological Organization (2023) STATE OF THE CLIMATE IN LATIN AMERICA AND THE CARIBBEAN 2022, No. 1322, 15–16 ("Drought also affected the west coast of subtropical South America, including Chile, where the last year with above average rainfall was 2006.51 The year 2022 was the fourth-driest year on record for Chile, which is experiencing a 14-year-long megadrought, the region's longest and most severe drought in more than 1000 years."). *See also* Masters J. & Henson B. (6 February 2024) *Chile's wildfire death toll rises above 130*, YALE CLIMATE CONNECTIONS ("The [February 2024] fires were stoked by near-record warm temperatures that have affected central Chile in recent weeks, with temperatures up to 42.9 degrees Celsius (109°F). The accompanying lack of rainfall has created extreme drought and very dangerous fire conditions. These conditions came on top of the Central Chile megadrought that began in 2010 — the region's longest drought in at least 1,000 years. This drought has brought precipitation 25-45% below average, lowering reservoirs and causing tensions and social unrest over water availability.").

[38] Masters J. & Henson B. (6 February 2024) *Chile's wildfire death toll rises above 130*, YALE CLIMATE CONNECTIONS ("Just last year, a severe drought with precipitation less than 50% of average hit central Chile. The drought was accompanied by the warmest February on record (up to 2 degrees Celsius above average). The exceptionally severe fire weather conditions that resulted led to a series of intense fires that caused over $880 million in damage (0.3% of GDP) and killed 26, making them Chile's deadliest wildfires on record. According to a 2024 study, six out of seven of Chile's most destructive fire seasons on record occurred since 2014. The study authors stated, "the concurrence of El Niño and climate-fueled droughts and heat waves boost the local fire risk and have decisively contributed to the intense fire activity recently seen in central Chile."); *discussing* Cordero R. R., Feron S., Damiani A., Carrasco J., Karas C., Wang C., Kraamwinkel C. T., & Beaulieu A. (2024) *Extreme fire weather in Chile driven by climate change and El Niño–Southern Oscillation (ENSO)*, SCI. REP. 14(1): 1–12, 3 ("During the exceptionally warm February 2023, the warmest on record in Central Chile, intense heatwaves pushed the daily maximum temperature well above typical

conditions (Fig. 4a). This contributed to making the austral summer 2022–2023 the second warmest on record (Fig. 4b). These records are likely part of a broader climate fueled trend. Five of the ten largest positive temperature anomalies in Central Chile have occurred since 2016 (Fig. 4b), and both heatwaves and "very warm" days have nearly tripled in recent decades (Fig. S5). The recordbreaking number of very warm days in February 2023 (Fig. 4c) contributed to extreme fire weather conditions seen in Central Chile the last season. On top of the recurring deficits in annual precipitation that have affected our study area in recent years (Fig. 4d,e), precipitation in Central Chile reached a new record low in January–February 2023 (Fig. 4f). … Yet, total precipitation in Central Chile in January–February 2023 was less than 3 mm, significantly below the 10–20 mm typically recorded in our study area in recent decades (Fig. 4f). The record-breaking drought in January–February 2023 (Fig. 4f) probably favored the last fierce fire season. The concurrence of severe droughts and persistent heatwaves, that led to the extreme fire weather conditions in Central Chile in February 2023, is becoming more frequent. Five of the ten largest positive FWI anomalies (relative to the 1981–2010 mean) occurred since 2014 (Fig. S6a). Ranked by frequency of extreme fire weather conditions, six of the ten worst seasons occurred since 2014 (Fig. S6b).").

[39] World Weather Attribution (24 January 2024) *Climate change, not El Niño, main driver of exceptional drought in highly vulnerable Amazon River Basin* ("In order to assess whether and to what extent human-induced climate change was a driver of this drought we combine observations-based data products and climate models and look at the 6 month meteorological (SPI6) drought as well as agricultural drought (SPEI6). We find that the likelihood of the meteorological drought occurring has increased by a factor of 10, while the agricultural drought has become about 30 times more likely. Using the US drought monitoring classification system, based on agricultural drought, this means that what is now classified an exceptional drought (D4), would have only been a 'severe drought' (D2) without the effects of climate change, caused by burning fossil fuels and deforestation. Unless the world rapidly stops burning fossil fuels and deforestation, these events will become even more common in the future. In a world 2°C warmer than preindustrial an event like this would become even more likely by a further factor of 4 for the agricultural drought (every 10-15 years) and a further factor of 3 for the meteorological drought (every ~30 years)."). *See also* Climate Central & World Weather Attribution (2024) *When Risks Become Reality: Extreme Weather In 2024*, 9.

[40] Gottlieb A. R. & Mankin J. S. (2024) *Evidence of human influence on Northern Hemisphere snow loss*, NATURE 625(7994): 293–300, 298–299 ("Under Shared Socioeconomic Pathway (SSP) 2–4.5, a 'middle-of-the-road' emissions scenario, the most highly populated basins are expected to see strong declines in spring runoff as a result of nonlinear snow loss, even in the face of relatively modest warming projected in those regions (Fig. 4b and Extended Data Fig. 8). … The western USA, for example, is poised to see particularly sharp spring runoff declines in the upper Mississippi (84 million people, 30.2% spring runoff decline), Colorado (14 million, 42.2%), Columbia (8.8 million, 32.7%) and San Joaquin (6.8 million, 40.9%) river basins (Extended Data Fig. 8).").

[41] World Meteorological Organization (29 November 2024) *Devastating Atlantic hurricane season comes to an end* ("Three hurricanes, in particular, were especially destructive. Hurricane Beryl was the earliest Atlantic basin Category-5 hurricane on record, with major impacts in the Caribbean. Hurricanes Helene and Milton caused catastrophic damage in the United States. The Atlantic basin saw 18 named storms in 2024. Eleven of those were hurricanes (winds of 74 mph or greater) and five intensified to major hurricanes of category 3, 4 or 5 on the Saffir Simpson scale, with winds of 178 kmh/111 mph or higher, according to the US National Oceanic and Atmospheric Administration (NOAA). It was the ninth successive season with above average activity. An average season produces 14 named storms, seven hurricanes and three major hurricanes.").

[42] Climate Central & World Weather Attribution (2024) *When Risks Become Reality: Extreme Weather In 2024*, 11 ("As the world warms, a greater proportion of the most powerful tropical cyclones are reaching category 3 or above, with much greater destructive potential. Hotter oceans are the main driver of increased intensity. Other aspects of tropical cyclones are also changing in different regions, with more storms undergoing rapid intensification, migrating poleward, and moving more slowly over land, often leading to more severe impacts. … Our studies found the rainfall from these two events [Hurricanes Helene and Milton] were made about 10% heavier by climate change, and the winds were about 5-6 m/s faster, while the warm sea surface temperatures that fueled the storms were more than 200 times as likely. A separate analysis by Climate Central found that climate change intensified every hurricane in 2024. The wind speeds were increased by 9-28 mph due to the influence of hotter oceans. It is unlikely Beryl and Milton

would have become category 5 hurricanes without climate change."), *citing* Gilford D. M., Giguere J., & Pershing A. J. (2024) *Human-caused ocean warming has intensified recent hurricanes*, ENVIRON. RES.: CLIMATE 3(4): 1–19.

[43] Climate Central & World Weather Attribution (2024) *When Risks Become Reality: Extreme Weather In 2024*, 11 ("The Philippines experienced a hyperactive late typhoon season. From mid-October to mid-November, six typhoons and a tropical storm affected Luzon island, the country's most populous island. The consecutive storms affected 13 million people and killed more than 160. Our study found the likelihood of three or more major typhoons (defined as category 3 or above) making landfall in the Philippines in a given year has increased by about 25% due to human-induced climate change.").

[44] Vautard R., Barnes C., Philip S., Kew S. F., Pinto I., & Otto F. E. L. (2024) *Heat extremes linearly shift with global warming, with frequency doubling per decade since 1979*, ENVIRON. RES. LETT. 19: 1–7, 4–5 ("However, exceedances of what would have been 1-in-10 year and 1-in-50 year events in the climate of 2000 have increased dramatically in the last two decades, and actually over time, with an exponential growth. The exponential fits give a doubling time of about 9 years for 50 year events and 14 years for 10 year events. … Overall the frequency of extreme heat events, taken in the 2000 warming context, have seen their frequencies quadruple in the last two decades."); 6 ("[W]e show that exceptional events with e.g. a frequency of 50 years at the beginning of the 21st century (2000) are now already becoming much less exceptional. Our results also show that despite a linear shift with global warming level, the frequency of high-amplitude heat extremes (highest daily temperature of the year) has been increasing exponentially globally with doubling times of about 9 years for 50 year events and 14 years for 10 year events. This is consistent with a less rapid relative change of frequencies as magnitude becomes less exceptional, which would hold with a shifting Gaussian distribution, for instance. This apparent paradox of a linear shift of frequency conditioned on the warming level at event year, and the exponentially increasing frequency when considering the reference of a fixed warming level can be explained by the rapid growth of probability in the shifting tail of distributions with external forcing, and not by an acceleration of global temperatures, which underwent a rather steady increase since 1979.").

[45] Climate Central & World Weather Attribution (2024) *When Risks Become Reality: Extreme Weather In 2024*, 6 ("Scientists at Climate Central calculated temperatures that people would consider hot based on their local experience: for each location in the dataset, we found the threshold temperature for the warmest 10% of temperatures observed over the 1991-2020 period (also referred to as the 90th percentile temperature). Days above this threshold are referred to as "dangerous heat days", as they correspond to a conservative approximation of the local minimum mortality temperature (MMT), an indicator of the local links between temperature and mortality. We then calculated the number of days that were hotter than this 90th percentile in 2024, and compared it to the number of days that would have been above the 90th percentile in a world without climate change (a more detailed methodology of how we did this is in our Heat Action Day report). Subtracting these two numbers, we were able to find in each location the number of days above the 90th percentile added by climate change in 2024. Additionally, we calculated this value on a country/territory by country/territory basis for the typical person in 220 countries or territories. We found that in 2024, the average person experienced 41 additional days of dangerous heat added by climate change. The regions with the highest number of added dangerous heat days were closest to the equator. Furthermore, the countries/territories with the highest number of dangerous heat days were overwhelmingly members of the Small Island Developing States (SIDS): 18 out of the top 20 countries that experienced the most added days of dangerous heat due to climate change were SIDS, whose residents experienced more than 130 additional risky heat days.").

[46] Arrighi J., Otto F. E. L., Pereira C., Philip S., Singh R., Vahlberg M., Giguere J., Pershing A., Tannenbaum A., & Veitch A. (2024) *Climate Change and the Escalation of Global Extreme Heat: Assessing and Addressing the Risks*, Climate Central, 1 ("Ahead of Heat Action Day, this new report from scientists at World Weather Attribution, the Red Cross Red Crescent Climate Centre, and Climate Central assesses the influence of human-caused climate change on dangerous heat waves over the past 12 months (May 15, 2023 to May 15, 2024). The period of analysis spans Earth's hottest year on record (2023) and 11 consecutive months of record-breaking global temperatures (June 2023-April 2024). … Over the 12-month period, 6.3 billion people (about 78% of the global population) experienced at least 31 days of extreme heat (hotter than 90% of temperatures observed in their local area over the 1991-2020 period) that was made at least two times more likely due to human-caused climate change.").

[47] Friedlingstein P., *et al.* (2025) *Global Carbon Budget 2024*, EARTH SYST. SCI. DATA 17(3): 965–1039, 969 ("The remaining carbon budget for a 50 % likelihood to limit global warming to 1.5, 1.7, and 2 °C above the 1850–1900 level has been reduced to 65 GtC (235 $GtCO_2$), 160 GtC (585 $GtCO_2$), and 305 GtC (1110 $GtCO_2$), respectively, from the beginning of 2025, equivalent to around 6, 14, and 27 years, assuming 2024 emissions levels.").

[48] The carbon budget calculates the amount of CO_2 that can still be emitted for a given likelihood (usually 50% or 67%) of staying below a temperature guardrail. Note that inclusion of sulfate reductions that would be expected to occur alongside reduced use of fossil fuels accounts for unmasking; *see* Forster P. M., *et al.* (2024) *Indicators of Global Climate Change 2023: annual update of key indicators of the state of the climate system and human influence*, EARTH SYST. SCI. DATA 16(6): 2625–2658, 2644–2645 ("The RCB for limiting warming to 1.5 °C is rapidly diminishing. It is important, however, to correctly interpret this information. RCB estimates consider projected reductions in non-CO_2 emissions that are aligned with a global ransition to net zero CO_2 emissions (Lamboll et al., 2023; Rogelj and Lamboll, 2024). These estimates assume median reductions in non-CO_2 emissions between 2020–2050 of CH_4 (about 50 %), N_2O (about 20 %) and SO_2 (about 80 %) (Rogelj and Lamboll, 2024) (see Sect. S8 and Table S5). … This year's update of the 1.5 °C budget uses the historical warming level for the 2014–2023 period of 1.19 °C, with a 0.13 °C future contribution of non-CO2 warming. Assuming a median estimate of 0.45 °C per 1000 Gt CO_2, this gives around 400 Gt CO_2 from the midpoint of the period, from which we subtract around 200 Gt CO_2 (205 Gt CO_2 emissions from the middle of the 2014–2023 period and 8 Gt CO_2 being the median estimate of the impact of Earth system feedbacks that would otherwise not be covered). This gives an RCB for 1.5 °C with 50 % probability of 200 Gt CO_2.").

[49] Forster P. M., *et al.* (2024) *Indicators of Global Climate Change 2023: annual update of key indicators of the state of the climate system and human influence*, EARTH SYST. SCI. DATA 16(6): 2625–2658, 2644 ("If these non-CO_2 greenhouse gas emission reductions are not achieved, the RCB will be smaller (see Lamboll et al., 2023; Rogelj and Lamboll, 2024)."). In the case of methane, holding emissions at today's levels over the next three decades will completely exhaust the carbon budget; *see* Rogelj J. & Lamboll R. D. (2024) *Substantial reductions in non-*CO_2 *greenhouse gas emissions reductions implied by IPCC estimates of the remaining carbon budget*, COMMUN. EARTH ENVIRON. 5: 1–5, 4 ("Assuming global CH4 emissions do not decline but instead are kept constant at 2020 levels would reduce the RCB by 431, 370, and 280 $GtCO_2$-we for RCBs compatible with 1.5 °C, 1.7 °C, and 2 °C, respectively. In other words, choosing not to reduce CH_4 emissions and correctly adjusting for this decision in RCB estimates would cause 1.5 °C compatible RCBs to be exhausted as of today (Fig. 1b, Table 1, Supplementary Tables S2, S5), in effect putting the 1.5 °C ambition of the Paris Agreement out of reach. Even a global 40% reduction between 2020 and 2040 would cause a 1.5 °C-compatible RCB reduction of about 60 $GtCO_2$-we, highlighting the importance of deep reductions in CH_4."). *See also* Shindell D., Sadavarte P., Aben I., Bredariol T. de O., Dreyfus G., Höglund-Isaksson L., Poulter B., Saunois M., Schmidt G. A., Szopa S., Rentz K., Parsons L., Qu Z., Faluvegi G., & Maasakkers J. D. (2024) *The methane imperative*, FRONT. SCI. 2: 1–28, 7 ("To have a two-thirds chance of staying below 2°C, the remaining CO_2 budget from 2020 is ~1150 GtCO2 (19), assuming roughly 35% reductions in methane by 2050. Every 100 Mt yr−1 of methane not permanently cut would take away about 300 $GtCO_2$ from the CO_2 budget over the next 50–100 years (63). This highlights the critical role of methane reductions in facilitating a plausible CO_2 reduction trajectory consistent with the Paris Agreement: the remaining carbon budget would otherwise become too small to make achieving those goals feasible (64, 65).").

[50] Forster P. M., et al. (2024) *Indicators of Global Climate Change 2023: annual update of key indicators of the state of the climate system and human influence*, EARTH SYST. SCI. DATA 16(6): 2625–2658, 2643–2644 ("The RCB is estimated by application of the WGI AR6 method described in Rogelj et al. (2019), which involves the combination of the assessment of five factors: (i) the most recent decade of human-induced warming (given in Sect. 7), (ii) the transient climate response to cumulative emissions of CO2 (TCRE), (iii) the zero emissions commitment (ZEC), (iv) the temperature contribution of non-CO2 emissions and (v) an adjustment term for Earth system feedbacks that are otherwise not captured through the other factors. AR6 WGI reassessed all five terms (Canadell et al., 2021). The incorporation of Earth system feedbacks was further considered by Lamboll and Rogelj (2022). Lamboll et al. (2023) further considered the temperature contribution of non-CO2 emissions, while Rogelj and Lamboll (2024) clarified the reductions in non-CO2 that are assumed in the RCB estimation.").

[51] Non-linear feedbacks and tipping points are not accounted for directly in the standard calculations for the carbon budget. The uncertainty around when tipping points will be crossed means that such events can only be accounted for using a leaner carbon budget that relies on stricter likelihoods; even then, accounting is incomplete. *See* Canadell J. G., *et al.* (2021) *Chapter 5: Global Carbon and other Biogeochemical Cycles and Feedbacks*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 739 ("There is *low confidence* in the estimate of the non-CO_2 biogeochemical feedbacks, due to the large range in the estimates of α for some individual feedbacks (Figure 5.29c), which can be attributed to the diversity in how models account for these feedbacks, limited process-level understanding, and the existence of known feedbacks for which there is not sufficient evidence to assess the feedback strength. … The applicability of the linear feedback framework (Section 5.4.5.5) suggests that large-scale biogeochemical feedbacks are approximately linear in the forcing from changes in CO_2 and climate. Nevertheless, regionally the biosphere is known to be capable of producing abrupt changes or even 'tipping points' (Higgins and Scheiter, 2012; Lasslop et al., 2016)."); Chen D., Rojas M., Samset B. H., Cobb K., Diongue Niang A., Edwards P., Emori S., Faria S. H., Hawkins E., Hope P., Huybrechts P., Meinshausen M., Mustafa S. K., Plattner G.-K., & Tréguier A.-M. (2021) *Chapter 1: Framing, Context and Methods*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.*, 202 ("Such paleoclimate evidence has even fuelled concerns that anthropogenic GHGs could tip the global climate into a permanent hot state (Steffen et al., 2018). However, there is no evidence of such non-linear responses at the global scale in climate projections for the next century, which indicate a near-linear dependence of global temperature on cumulative GHG emissions (Section 1.3.5, Chapter 5, Section 5.5 and Chapter 7, Section 7.4.3.1). At the regional scale, abrupt changes and tipping points, such as Amazon forest dieback and permafrost collapse, have occurred in projections with Earth System Models (Drijfhout et al., 2015; Bathiany et al., 2020; Chapter 4, Section 4.7.3). In such simulations, tipping points occur in narrow regions of parameter space (e.g., CO_2 concentration or temperature increase), and for specific climate background states. This makes them difficult to predict using ESMs relying on parmeterizations of known processes. In some cases, it is possible to detect forthcoming tipping points through time-series analysis that identifies increased sensitivity to perturbations as the tipping point is approached (e.g., 'critical slowing-down', Scheffer et al., 2012)."); *and* Bathiany S., Hidding J., & Scheffer M. (2020) *Edge Detection Reveals Abrupt and Extreme Climate Events*, J. CLIM. 33(15): 6399–6421, 6416 ("Despite their societal relevance, our knowledge about the risks of future abrupt climate shifts is far from robust. Several important aspects are highly uncertain: future greenhouse gas emissions (scenario uncertainty), the current climate state (initial condition uncertainty), the question whether and how to model specific processes (structural uncertainty), and what values one should choose for parameters appearing in the equations (parametric uncertainty). Such uncertainties can be explored using ensemble simulations. For example, by running many simulations with different combinations of parameter values a perturbed-physics ensemble can address how parameter uncertainty affects the occurrence of extreme events (Clark et al. 2006). This strategy can be particularly beneficial for studying abrupt events as well since abrupt shifts are associated with region-specific processes, whereas models are usually calibrated to produce a realistic global mean climate at the expense of regional realism (Mauritsen et al. 2012; McNeall et al. 2016). The currently available model configurations are therefore neither reliable nor sufficient to assess the risk of abrupt shifts (Drijfhout et al. 2015). It is hence very plausible that yet-undiscovered tipping points can occur in climate models.").

[52] Lenton T. M., Rockstrom J., Gaffney O., Rahmstorf S., Richardson K., Steffen W., & Schellnhuber H. J. (2019) *Climate tipping points—too risky to bet against*, Comment, NATURE 575(7784): 592–595, 594 ("The world's remaining emissions budget for a 50:50 chance of staying within 1.5 °C of warming is only about 500 gigatonnes (Gt) of CO_2. Permafrost emissions could take an estimated 20% (100 Gt CO_2) off this budget[10], and that's without including methane from deep permafrost or undersea hydrates. If forests are close to tipping points, Amazon dieback could release another 90 Gt CO_2 and boreal forests a further 110 Gt CO_2 (ref. 11). With global total CO_2 emissions still at more than 40 Gt per year, the remaining budget could be all but erased already."). Note that continuing emissions since this analysis was published have depleted the remaining carbon budget below the 500 GtCO_2 estimated in 2019.

[53] United Nations Framework Convention on Climate Change (8 September 2023) *Technical dialogue of the first global stocktake*, Synthesis report by the co-facilitators on the technical dialogue, Subsidiary Body for Scientific and Technological Advice & Subsidiary Body for Implementation, 59th Session, FCCC/SB/2023/9, 5 ("9. Key finding 4:

global emissions are not in line with modelled global mitigation pathways consistent with the temperature goal of the Paris Agreement, and there is a rapidly narrowing window to raise ambition and implement existing commitments in order to limit warming to 1.5 °C above pre-industrial levels. 10. All Parties to the Paris Agreement have communicated NDCs that include mitigation targets and/or measures. A growing number of Parties have also communicated LT-LEDS. Emissions gaps are the difference between the emission levels implied by the NDCs and the average emission levels of global modelled mitigation pathways consistent with limiting warming to 1.5 °C or 2 °C. Implementation gaps refer to how far currently enacted policies and actions fall short of reaching stated targets. Based on current NDCs, the gap to emissions consistent with limiting warming to 1.5 °C in 2030 is estimated to be 20.3–23.9 Gt CO_2 eq.2"). *See also* United Nations Environment Programme (2024) EMISSIONS GAP REPORT 2024, xiii ("Under current policies, global 2030 emissions are projected to be 57 $GtCO_2e$ (range: 53–59), which is slightly higher than last year's assessment, and around 2 $GtCO_2e$ (range: 0–3 GtCO2e) above the unconditional NDCs and 5 $GtCO_2e$ (range: 2–9 $GtCO_2e$) above the conditional NDCs (table ES.2). This gap in implementation of policies to achieve the NDCs for 2030 is about the same as in last year's assessment."); *and* Pearce F. (21 March 2024) *Nations Are Undercounting Emissions, Putting UN Goals at Risk*, YALE ENVIRONMENT 360 ("But the national inventories of emissions supplied to the United Nations climate convention (UNFCCC) by most countries are anything but reliable, according to a growing body of research. The data supplied to the UNFCCC, and published on its website, are typically out of date, inconsistent, and incomplete. For most countries, "I would not put much value, if any, on the submissions," says Glen Peters of the Centre for International Climate Research in Norway, a longtime analyst of emissions trends. The data from large emitters is as much open to questions as that from smaller and less industrialised nations.").

[54] United Nations Environment Programme (2024) EMISSIONS GAP REPORT 2024, 34 (*see* "Figure 4.2 Projections of global warming under the pledge-based scenarios assessed in this chapter" showing "Unconditional NDCs continuing" with a projection of 2.6°C [1.8–3.4°C] for a 50% chance.).

[55] Möller T., Högner A., Schleussner C.-F., Bien S., Kitzmann N., Lamboll R., Rogelj J., Donges J., Rockström J., & Wunderling N. (2023) *Achieving net zero greenhouse gas emissions critical to limit climate tipping risks*, NAT. COMMUN. 15(1): 1–11, 5–6 ("Our study reveals that following current climate policies until 2100 may lead to high tipping risks even if long-term temperatures return to 1.5 °C by 2300. Under such an emission pathway, we report a tipping probability of 45% (median estimate, 10–90% range: 23–71%) until 2300 and of 76% (median estimate, 10–90% range: 39–98%) in the long term. Scenarios following pledged NDCs under the UNFCCC in 2020 until 2100 fail to adhere to the Paris Agreement LTTG [long-term temperature goal], and even when subsequently designed such that temperatures return to 1.5 °C (median) after overshoot, we find that they are insufficient to avoid tipping risks (median estimate: 30%, 10–90% range: 10–56% until 2300)."). *See also* Ripple W. J., Wolf C., Gregg J. W., Rockström J., Mann M. E., Oreskes N., Lenton T. M., Rahmstorf S., Newsome T. M., Xu C., Svenning J.-C., Pereira C. C., Law B. E., & Crowther T. W. (2024) *The 2024 state of the climate report: Perilous times on planet Earth*, BIOSCI.: 1–13.

[56] Molina M., Zaelke D., Sarma K. M., Andersen S. O., Ramanathan V., & Kaniaru D. (2009) *Reducing abrupt climate change risk using the Montreal Protocol and other regulatory actions to complement cuts in* CO_2 *emissions*, PROC. NAT'L. ACAD. SCI. 106(49): 20616–20621, 20616 ("Current emissions of anthropogenic greenhouse gases (GHGs) have already committed the planet to an increase in average surface temperature by the end of the century that may be above the critical threshold for tipping elements of the climate system into abrupt change with potentially irreversible and unmanageable consequences. This would mean that the climate system is close to entering if not already within the zone of "dangerous anthropogenic interference" (DAI). Scientific and policy literature refers to the need for "early," "urgent," "rapid," and "fast-action" mitigation to help avoid DAI and abrupt climate changes. We define "fast-action" to include regulatory measures that can begin within 2–3 years, be substantially implemented in 5–10 years, and produce a climate response within decades. We discuss strategies for short-lived non-CO_2 GHGs and particles, where existing agreements can be used to accomplish mitigation objectives. Policy makers can amend the Montreal Protocol to phase down the production and consumption of hydrofluorocarbons (HFCs) with high global warming potential. Other fast-action strategies can reduce emissions of black carbon particles and precursor gases that lead to ozone formation in the lower atmosphere, and increase biosequestration, including through biochar. These and other fast-action strategies may reduce the risk of abrupt climate change in the next few decades by complementing cuts in CO_2 emissions."). *See also* Molina M., Ramanathan V. & Zaelke D. (2020) *Best path to net zero: Cut short-lived climate pollutants*, BULLETIN OF THE ATOMIC SCIENTISTS ("And let us be clear: By "speed," we mean measures—

including regulatory ones—that can begin within two-to-three years, be substantially implemented in five-to-10 years, and produce a climate response within the next decade or two.").

[57] Intergovernmental Panel on Climate Change (2023) AR6 SYNTHESIS REPORT: CLIMATE CHANGE 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 36 ("In terrestrial ecosystems, 3–14% of the tens of thousands of species assessed will likely face a very high risk of extinction at a GWL of 1.5°C. Coral reefs are projected to decline by a further 70–90% at 1.5°C of global warming (*high confidence*). At this GWL, many low-elevation and small glaciers around the world would lose most of their mass or disappear within decades to centuries (*high confidence*). Regions at disproportionately higher risk include Arctic ecosystems, dryland regions, small island development states and Least Developed Countries (*high confidence*)."). *See also* Watts N., *et al.* (2021) *The 2020 report of The Lancet Countdown on health and climate change: responding to converging crises*, THE LANCET 397(10269): 129–170, 129 ("Vulnerable populations were exposed to an additional 475 million heatwave events globally in 2019, which was, in turn, reflected in excess morbidity and mortality (indicator 1.1.2). During the past 20 years, there has been a 53.7% increase in heat-related mortality in people older than 65 years, reaching a total of 296 000 deaths in 2018 (indicator 1.1.3). The high cost in terms of human lives and suffering is associated with effects on economic output, with 302 billion h of potential labour capacity lost in 2019 (indicator 1.1.4). India and Indonesia were among the worst affected countries, seeing losses of potential labour capacity equivalent to 4–6% of their annual gross domestic product (indicator 4.1.3)."); Atwoli L., *et al.* (2021) *Call for emergency action to limit global temperature increases, restore biodiversity, and protect health*, THE LANCET 398(10304): 939–941, 939 ("Harms disproportionately affect the most vulnerable, including children, older populations, ethnic minorities, poorer communities, and those with underlying health problems."); Xu C., Kohler T. A., Lenton T. M., Svenning J.-C., & Scheffer M. (2020) *Future of the human climate niche*, PROC. NAT'L. ACAD. SCI. 117(21): 11350–11355, 11350 ("Here, we demonstrate that for millennia, human populations have resided in the same narrow part of the climatic envelope available on the globe, characterized by a major mode around ~11 °C to 15 °C mean annual temperature (MAT). …We show that in a business-as-usual climate change scenario, the geographical position of this temperature niche is projected to shift more over the coming 50 y than it has moved since 6000 BP. … Specifically, 3.5 billion people will be exposed to MAT ≥29.0 °C, a situation found in the present climate only in 0.8% of the global land surface, mostly concentrated in the Sahara, but in 2070 projected to cover 19% of the global land (Fig. 3). … For instance, accounting for population growth projected in the SSP3 scenario, each degree of temperature rise above the current baseline roughly corresponds to one billion humans left outside the temperature niche, absent migration (*SI Appendix*, Fig. S14)."); *and* Xu Y. & Ramanathan V. (2017) *Well below 2 °C: Mitigation strategies for avoiding dangerous to catastrophic climate changes*, PROC. NAT'L. ACAD. SCI. 114(39): 10319–10323, 10320 ("Box 2. Risk Categorization of Climate Change to Society. … [A] 2 °C warming would double the land area subject to deadly heat and expose 48% of the population. A 4 °C warming by 2100 would subject 47% of the land area and almost 74% of the world population to deadly heat, which could pose existential risks to humans and mammals alike unless massive adaptation measures are implemented, such as providing air conditioning to the entire population or a massive relocation of most of the population to safer climates. … This bottom 3 billion population comprises mostly subsistent farmers, whose livelihood will be severely impacted, if not destroyed, with a one- to five-year megadrought, heat waves, or heavy floods; for those among the bottom 3 billion of the world's population who are living in coastal areas, a 1- to 2-m rise in sea level (likely with a warming in excess of 3 °C) poses existential threat if they do not relocate or migrate. It has been estimated that several hundred million people would be subject to famine with warming in excess of 4 °C (54). However, there has essentially been no discussion on warming beyond 5 °C. Climate change-induced species extinction is one major concern with warming of such large magnitudes (>5 °C). The current rate of loss of species is ~1,000-fold the historical rate, due largely to habitat destruction. At this rate, about 25% of species are in danger of extinction in the coming decades (56). Global warming of 6 °C or more (accompanied by increase in ocean acidity due to increased CO_2) can act as a major force multiplier and expose as much as 90% of species to the dangers of extinction (57). The bodily harms combined with climate change-forced species destruction, biodiversity loss, and threats to water and food security, as summarized recently (58), motivated us to categorize warming beyond 5 °C as unknown??, implying the possibility of existential threats.").

[58] Goldstein A., Noon M. L., Ledezma J. C., Roehrdanz P. R., Raghav S., McGreevey M., Stone C., Shrestha S., Golden Kroner R., Hole D., & Turner W. (2021) IRRECOVERABLE CARBON: THE PLACES WE MUST PROTECT TO AVERT CLIMATE CATASTROPHE, Conservation International, 7 ("'Irrecoverable carbon' refers to the vast stores of carbon in nature that are vulnerable to release from human activity and, if lost, could not be restored by 2050 — when the world must reach net-zero emissions to avoid the worst impacts of climate change. There are high concentrations of irrecoverable carbon in the Amazon (31.5 Gt), the Congo Basin (8.1 Gt), and New Guinea (7.3 Gt). Other important irrecoverable carbon reserves are located in the Pacific Northwest of North America, the Valdivian forests of Chile, the mangroves and swamp forests of Guyana, the peatlands of Northern Scotland, Niger Delta's mangroves, Cambodia's Tonle Sap Lake, the Scandinavian and Siberian boreal forests, and the eucalyptus forest of Southeast Australia, among others."). *See also* Griscom B. W., *et al.* (2017) *Natural climate solutions*, PROC. NAT'L. ACAD. SCI. 114(44): 11645–11650, 11645 ("Better stewardship of land is needed to achieve the Paris Climate Agreement goal of holding warming to below 2 °C; however, confusion persists about the specific set of land stewardship options available and their mitigation potential. To address this, we identify and quantify "natural climate solutions" (NCS): 20 conservation, restoration, and improved land management actions that increase carbon storage and/or avoid greenhouse gas emissions across global forests, wetlands, grasslands, and agricultural lands. We find that the maximum potential of NCS—when constrained by food security, fiber security, and biodiversity conservation—is 23.8 petagrams of CO_2 equivalent ($PgCO_2e$) y^{-1} (95% CI 20.3–37.4). This is ≥30% higher than prior estimates, which did not include the full range of options and safeguards considered here. About half of this maximum (11.3 $PgCO_2e$ y^{-1}) represents cost-effective climate mitigation, assuming the social cost of CO_2 pollution is ≥100 USD $MgCO_2e^{-1}$ by 2030. Natural climate solutions can provide 37% of cost-effective CO_2 mitigation needed through 2030 for a >66% chance of holding warming to below 2 °C. One-third of this cost-effective NCS mitigation can be delivered at or below 10 USD $MgCO_2^{-1}$. Most NCS actions—if effectively implemented—also offer water filtration, flood buffering, soil health, biodiversity habitat, and enhanced climate resilience. Work remains to better constrain uncertainty of NCS mitigation estimates. Nevertheless, existing knowledge reported here provides a robust basis for immediate global action to improve ecosystem stewardship as a major solution to climate change."); Goldstein A., *et al.* (2020) *Protecting irrecoverable carbon in Earth's ecosystems*, NAT. CLIM. CHANGE 10(4): 287–295; *and* Noon M. L., Goldstein A., Ledezma J. C., Roehrdanz P. R., Cook-Patton S. C., Spawn-Lee S. A., Wright T. M., Gonzalez-Roglich M., Hole D. G., Rockström J., & Turner W. R. (2021) Mapping the irrecoverable carbon in Earth's ecosystems, NAT. SUSTAIN. 5: 37–46.

[59] Armstrong McKay D. I., Staal A., Abrams J. F., Winkelmann R., Sakschewski B., Loriani S., Fetzer I., Cornell S. E., Rockström J., & Lenton T. M. (2022) *Exceeding 1.5°C global warming could trigger multiple climate tipping points*, SCIENCE 377(6611): 1–10, 1–2 ("Notably, Arctic summer sea ice loss involves the positive ice-albedo feedback, but unlike yearround sea ice loss, that feedback alone is not strong enough to produce a clear threshold beyond which loss would continue even if global warming stopped (20, 21). Consequently, we describe such feedbacks as "threshold-free".").

[60] Ripple W. J., Wolf C., Gregg J. W., Rockström J., Mann M. E., Oreskes N., Lenton T. M., Rahmstorf S., Newsome T. M., Xu C., Svenning J.-C., Pereira C. C., Law B. E., & Crowther T. W. (2024) *The 2024 state of the climate report: Perilous times on planet Earth*, BIOSCI.: 1–13, 9 ("Tipping elements are biophysical systems on Earth with tipping point behavior that contribute to regulating the climate system (Lenton et al. 2008). They have recently been assessed for their tipping sensitivity. Five of sixteen climate tipping elements are likely to cross their tipping points at 1.5°C: the Greenland ice sheet, the West Antarctic ice sheet, boreal permafrost, low-latitude coral reefs, and the Barents Sea Ice (Armstrong McKay et al. 2022). Several climate tipping elements are connected, and if one tips, others may tip, triggering a tipping point cascade (Wunderling et al. 2024). Overall, this points to a complex situation where climate controlling feedback loops and tipping point systems are interconnected in a way that could trigger self-perpetuating processes that amplify warming beyond human control."). *See also* Armstrong McKay D. I., Staal A., Abrams J. F., Winkelmann R., Sakschewski B., Loriani S., Fetzer I., Cornell S. E., Rockström J., & Lenton T. M. (2022*) Exceeding 1.5°C global warming could trigger multiple climate tipping points*, SCIENCE 377(6611): 1–10, 7 ("The chance of triggering CTPs is already non-negligible and will grow even with stringent climate mitigation (SSP1-1.9 in Fig. 2, B and C). Nevertheless, achieving the Paris Agreement's aim to pursue efforts to limit warming to 1.5°C would clearly be safer than keeping global warming below 2°C (90) (Fig. 2). Going from 1.5 to 2°C increases the likelihood of committing to WAIS and GrIS collapse near complete warm-water coral die-off, and abrupt permafrost thaw; further,

the best estimate threshold for LABC collapse is crossed. The likelihood of triggering AMOC collapse, Boreal forest shifts, and extra-polar glacier loss becomes non-negligible at >1.5°C and glacier loss becomes likely by ~2°C. A cluster of abrupt shifts occur in ESMs at 1.5 to 2°C (19). Although not tipping elements, ASSI loss could become regular by 2°C, gradual permafrost thaw would likely become widespread beyond 1.5°C, and land carbon sink weakening would become significant by 2°C."). *And see* Lenton T. M., Rockstrom J., Gaffney O., Rahmstorf S., Richardson K., Steffen W., & Schellnhuber H. J. (2019) *Climate tipping points—too risky to bet against*, Comment, NATURE 575(7784): 592–595, 594 ("In our view, the clearest emergency would be if we were approaching a global cascade of tipping points that led to a new, less habitable, 'hothouse' climate state[11]. Interactions could happen through ocean and atmospheric circulation or through feedbacks that increase greenhouse-gas levels and global temperature. Alternatively, strong cloud feedbacks could cause a global tipping point[12,13].We argue that cascading effects might be common. Research last year[14] analysed 30 types of regime shift spanning physical climate and ecological systems, from collapse of the West Antarctic ice sheet to a switch from rainforest to savanna. This indicated that exceeding tipping points in one system can increase the risk of crossing them in others. Such links were found for 45% of possible interactions[14]. In our view, examples are starting to be observed. … If damaging tipping cascades can occur and a global tipping point cannot be ruled out, then this is an existential threat to civilization. No amount of economic cost–benefit analysis is going to help us. We need to change our approach to the climate problem. … In our view, the evidence from tipping points alone suggests that we are in a state of planetary emergency: both the risk and urgency of the situation are acute…."); Steffen W., *et al*. (2018) *Trajectories of the Earth System in the Anthropocene*, PROC. NAT'L. ACAD. SCI. 115(33): 8252–8259, 8254 ("This analysis implies that, even if the Paris Accord target of a 1.5 °C to 2.0 °C rise in temperature is met, we cannot exclude the risk that a cascade of feedbacks could push the Earth System irreversibly onto a "Hothouse Earth" pathway. The challenge that humanity faces is to create a "Stabilized Earth" pathway that steers the Earth System away from its current trajectory toward the threshold beyond which is Hothouse Earth (Fig. 2). The human-created Stabilized Earth pathway leads to a basin of attraction that is not likely to exist in the Earth System's stability landscape without human stewardship to create and maintain it. Creating such a pathway and basin of attraction requires a fundamental change in the role of humans on the planet. This stewardship role requires deliberate and sustained action to become an integral, adaptive part of Earth System dynamics, creating feedbacks that keep the system on a Stabilized Earth pathway (Alternative Stabilized Earth Pathway)."); *and* Intergovernmental Panel on Climate Change (2023) AR6 SYNTHESIS REPORT: CLIMATE CHANGE 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 36, 42 ("In terrestrial ecosystems, 3–14% of the tens of thousands of species assessed will likely face a very high risk of extinction at a GWL of 1.5°C. Coral reefs are projected to decline by a further 70–90% at 1.5°C of global warming (*high confidence*). At this GWL, many low-elevation and small glaciers around the world would lose most of their mass or disappear within decades to centuries (*high confidence*). Regions at disproportionately higher risk include Arctic ecosystems, dryland regions, small island development states and Least Developed Countries (*high confidence*). … The likelihood of abrupt and irreversible changes and their impacts increase with higher global warming levels (*high confidence*). As warming levels increase, so do the risks of species extinction or irreversible loss of biodiversity in ecosystems such as forests (*medium confidence*), coral reefs (*very high confidence*) and in Arctic regions (*high confidence*). Risks associated with large-scale singular events or tipping points, such as ice sheet instability or ecosystem loss from tropical forests, transition to high risk between 1.5°C–2.5°C (*medium confidence*) and to very high risk between 2.5°C–4°C (*low confidence*). The response of biogeochemical cycles to anthropogenic perturbations can be abrupt at regional scales and irreversible on decadal to century time scales (*high confidence*). The probability of crossing uncertain regional thresholds increases with further warming (*high confidence*).").

[61] Ripple W. J., Wolf C., Gregg J. W., Rockström J., Mann M. E., Oreskes N., Lenton T. M., Rahmstorf S., Newsome T. M., Xu C., Svenning J.-C., Pereira C. C., Law B. E., & Crowther T. W. (2024) *The 2024 state of the climate report: Perilous times on planet Earth*, BIOSCI.: 1–13, 9 ("Tipping elements are biophysical systems on Earth with tipping point behavior that contribute to regulating the climate system (Lenton et al. 2008). They have recently been assessed for their tipping sensitivity. Five of sixteen climate tipping elements are likely to cross their tipping points at 1.5°C: the Greenland ice sheet, the West Antarctic ice sheet, boreal permafrost, low-latitude coral reefs, and the Barents Sea Ice (Armstrong McKay et al. 2022). Several climate tipping elements are connected, and if one tips, others may tip, triggering a tipping point cascade (Wunderling et al. 2024). Overall, this points to a complex situation where climate

controlling feedback loops and tipping point systems are interconnected in a way that could trigger self-perpetuating processes that amplify warming beyond human control."). *See also* Armstrong McKay D. I., Staal A., Abrams J. F., Winkelmann R., Sakschewski B., Loriani S., Fetzer I., Cornell S. E., Rockström J., & Lenton T. M. (2022) *Exceeding 1.5°C global warming could trigger multiple climate tipping points*, SCIENCE 377(6611): 1–10, 7 ("Current warming is ~1.1°C above preindustrial and even with rapid emission cuts warming will reach ~1.5°C by the 2030s (23). We cannot rule out that WAIS [West Antarctic Ice Sheet] and GrIS [Greenland Ice Sheet] tipping points have already been passed (see above) and several other tipping elements have minimum threshold values within the 1.1 to 1.5°C range. Our best estimate thresholds for GrIS, WAIS, REEF [low-latitude coral reefs], and North Atlantic subpolar gyre / Labrador-Irminger Sea convection abrupt permafrost thaw (PFAT) are ~1.5°C although WAIS and GrIS collapse may still be avoidable if GMST [Global Mean Surface Temperature] returns below 1.5°C within an uncertain overshoot time (likely decades) (94). … The chance of triggering CTPs [climate tipping points] is already non-negligible and will grow even with stringent climate mitigation (SSP1-1.9 in Fig. 2, B and C). Nevertheless, achieving the Paris Agreement's aim to pursue efforts to limit warming to 1.5°C would clearly be safer than keeping global warming below 2°C (90) (Fig. 2). Going from 1.5 to 2°C increases the likelihood of committing to WAIS and GrIS collapse near complete warm-water coral die-off, and abrupt permafrost thaw; further, the best estimate threshold for LABC [North Atlantic subpolar gyre / Labrador-Irminger Sea convection] collapse is crossed. The likelihood of triggering AMOC [Atlantic Meridional Overturning Circulation] collapse, Boreal forest shifts, and extra-polar glacier loss becomes non-negligible at >1.5°C and glacier loss becomes likely by ~2°C. A cluster of abrupt shifts occur in ESM [Earth System Models] at 1.5 to 2°C (19). Although not tipping elements, ASSI [Arctic Summer Sea Ice] loss could become regular by 2°C, gradual permafrost thaw would likely become widespread beyond 1.5°C, and land carbon sink weakening would become significant by 2°C."); Intergovernmental Panel on Climate Change (2023) AR6 SYNTHESIS REPORT: CLIMATE CHANGE 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 42 ("Risks associated with large-scale singular events or tipping points, such as ice sheet instability or ecosystem loss from tropical forests, transition to high risk between 1.5°C–2.5°C (medium confidence) and to very high risk between 2.5°C–4°C (low confidence). The response of biogeochemical cycles to anthropogenic perturbations can be abrupt at regional scales and irreversible on decadal to century time scales (high confidence). The probability of crossing uncertain regional thresholds increases with further warming (high confidence).").

[62] Intergovernmental Panel on Climate Change (2023) AR6 SYNTHESIS REPORT: CLIMATE CHANGE 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 36 ("At 2°C of global warming, overall risk levels associated with the unequal distribution of impacts (RFC3), global aggregate impacts (RFC4) and large-scale singular events (RFC5) would be transitioning to high (medium confidence), those associated with extreme weather events (RFC2) would be transitioning to very high (medium confidence), and those associated with unique and threatened systems (RFC1) would be very high (high confidence) (Figure 3.3, panel a). With about 2°C warming, climate-related changes in food availability and diet quality are estimated to increase nutrition-related diseases and the number of undernourished people, affecting tens (under low vulnerability and low warming) to hundreds of millions of people (under high vulnerability and high warming), particularly among low-income households in low- and middle-income countries in sub-Saharan Africa, South Asia and Central America (high confidence). For example, snowmelt water availability for irrigation is projected to decline in some snowmelt dependent river basins by up to 20% (medium confidence). Climate change risks to cities, settlements and key infrastructure will rise sharply in the mid- and long-term with further global warming, especially in places already exposed to high temperatures, along coastlines, or with high vulnerabilities (high confidence). … [FOONOTE 64]: The Reasons for Concern (RFC) framework communicates scientific understanding about accrual of risk for five broad categories {WGII Figure SPM.3}. RFC1: Unique and threatened systems: ecological and human systems that have restricted geographic ranges constrained by climate-related conditions and have high endemism or other distinctive properties. Examples include coral reefs, the Arctic and its Indigenous Peoples, mountain glaciers and biodiversity hotspots. RFC2: Extreme weather events: risks/impacts to human health, livelihoods, assets and ecosystems from extreme weather events such as heatwaves, heavy rain, drought and associated wildfires, and coastal flooding. RFC3: Distribution of impacts: risks/impacts that disproportionately affect particular groups due to uneven distribution of physical climate change

hazards, exposure or vulnerability. RFC4: Global aggregate impacts: impacts to socioecological systems that can be aggregated globally into a single metric, such as monetary damages, lives affected, species lost or ecosystem degradation at a global scale. RFC5: Large-scale singular events: relatively large, abrupt and sometimes irreversible changes in systems caused by global warming, such as ice sheet instability or thermohaline circulation slowing.").

[63] Lenton T. M., *et al.* (eds.) (2023) *Summary Report*, in GLOBAL TIPPING POINTS REPORT 2023, 13.

[64] Lenton T. M., *et al.* (eds.) (2023) *Summary Report*, *in* GLOBAL TIPPING POINTS REPORT 2023, 13 ("Early warning signals have been detected that are consistent with the Greenland Ice Sheet, AMOC, and Amazon rainforest heading towards tipping points.").

[65] Armstrong McKay D. I. & Loriani S. (eds.) (2023) *Section 1: Earth systems tipping points*, *in* GLOBAL TIPPING POINTS REPORT 2023, Lenton T. M., et al. (eds.), 7 ("Our Earth system tipping point (ESTP) definition: Tipping points occur when change in a tipping system (also known as a tipping element) becomes self-sustaining once a forcing threshold is passed, leading to a qualitative state change (e.g. an ecological regime shift) driven by one or more positive/amplifying feedback loops. Climate tipping points, for example, occur when parts of the climate system reach global warming thresholds beyond which positive/amplifying feedbacks propel a shift to a totally different state, such as the inevitable collapse of an ice sheet or shutdown of a deep ocean convection site (Figure 1.1.2)."). *See also* Armstrong McKay D. I., Staal A., Abrams J. F., Winkelmann R., Sakschewski B., Loriani S., Fetzer I., Cornell S. E., Rockström J., & Lenton T. M. (2022) *Exceeding 1.5°C global warming could trigger multiple climate tipping points*, SCIENCE 377(6611): 1–10, 1 ("Here, our specific definition is as follows: Tipping points occur when change in part of the climate system becomes (i) self perpetuating beyond (ii) a warming threshold as a result of asymmetry in the relevant feedbacks, leading to (iii) substantial and widespread Earth system impacts. Self-perpetuation is usually due to positive feedback within a system attaining sufficient strength to overcome stabilizing negative feedbacks and (temporarily) reach a "runaway" condition (in which an initial change propagating around a feedback loop gives rise to an additional change that is at least as large as the initial change and so on). Most positive feedbacks never attain this condition and instead simply amplify the original driver in a constrained way.").

[66] Intergovernmental Panel on Climate Change (2018) *Summary for Policymakers*, *in* GLOBAL WARMING OF 1.5 °C, Special Report of the Intergovernmental Panel on Climate Change, Masson-Delmotte V., et al. (eds.), 12 ("In model pathways with no or limited overshoot of 1.5 °C, global net anthropogenic CO_2 emissions decline by about 45% from 2010 levels by 2030 (40–60% interquartile range), reaching net zero around 2050 (2045–2055 interquartile range)…. Modelled pathways that limit global warming to 1.5 °C with no or limited overshoot involve deep reductions in emissions of methane and black carbon (35% or more of both by 2050 relative to 2010). … C.3. All pathways that limit global warming to 1.5 °C with limited or no overshoot project the use of carbon dioxide removal (CDR) on the order of 100–1000 $GtCO_2$ over the 21st century.").

[67] Lelieveld J., Klingmüller K., Pozzer A., Burnett R. T., Haines A., & Ramanathan V. (2019) *Effects of fossil fuel and total anthropogenic emission removal on public health and climate*, PROC. NAT'L. ACAD. SCI. 116(15): 7192–7197, 7194 ("Finally, our model simulations show that fossil-fuel-related aerosols have masked about 0.51(±0.03) °C of the global warming from increasing greenhouse gases (Fig. 3). The largest temperature impacts are found over North America and Northeast Asia, being up to 2 °C. By removing all anthropogenic emissions, a mean global temperature increase of 0.73(±0.03) °C could even warm some regions up to 3 °C. Since the temperature increase from past CO_2 emissions is irreversible on human timescales, the aerosol warming will be unleashed during the phaseout (11, 19–22)."). *See also* Intergovernmental Panel on Climate Change (2021) *Summary for Policymakers*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 7 (Figure SPM.2c shows that Sulphur dioxide (SO_2) contributes –0.49 °C (–0.10 to –0.93 °C) to observed warming in 2010–2019 relative to 1850–1900); Samset B. H., Sand M., Smith C. J., Bauer S. E., Forster P. M., Fuglestvedt J. S., Osprey S., & Schleussner C.-F. (2018) *Climate impacts from a removal of anthropogenic aerosol emissions*, GEOPHYS. RES. LETT. 45(2): 1020–1029, 1020 ("Limiting global warming to 1.5 or 2.0°C requires strong mitigation of anthropogenic greenhouse gas (GHG) emissions. Concurrently, emissions of anthropogenic aerosols will decline, due to coemission

with GHG, and measures to improve air quality. … Removing aerosols induces a global mean surface heating of 0.5–1.1°C, and precipitation increase of 2.0–4.6%. Extreme weather indices also increase. We find a higher sensitivity of extreme events to aerosol reductions, per degree of surface warming, in particular over the major aerosol emission regions. … "Plain Language Summary. To keep within 1.5 or 2° of global warming, we need massive reductions of greenhouse gas emissions. At the same time, aerosol emissions will be strongly reduced. We show how cleaning up aerosols, predominantly sulfate, may add an additional half a degree of global warming, with impacts that strengthen those from greenhouse gas warming. The northern hemisphere is found to be more sensitive to aerosol removal than greenhouse gas warming, because of where the aerosols are emitted today. This means that it does not only matter whether or not we reach international climate targets. It also matters how we get there."); *and* Feijoo F., Mignone B. K., Kheshgi H. S., Hartin C., McJeon H., & Edmonds J. (2019) *Climate and carbon budget implications of linked future changes in* CO_2 *and non-*CO_2 *forcing*, ENVIRON. RES. LETT. 14(4): 1–11.

[68] Dreyfus G. B., Xu Y., Shindell D. T., Zaelke D., & Ramanathan V. (2022) *Mitigating climate disruption in time: A self-consistent approach for avoiding both near-term and long-term global warming*, PROC. NAT'L. ACAD. SCI. 119(22): 1–8, 1 ("We find that mitigation measures that target only decarbonization are essential for strong long-term cooling but can result in weak near-term warming (due to unmasking the cooling effect of co-emitted aerosols) and lead to temperatures exceeding 2°C before 2050. In contrast, pairing decarbonization with additional mitigation measures targeting short-lived climate pollutants (SLCPs) and N_2O, slows the rate of warming a decade or two earlier than decarbonization alone and avoids the 2°C threshold altogether. These non-CO_2 targeted measures when combined with decarbonization can provide net cooling by 2030, reduce the rate of warming from 2030 to 2050 by about 50%, roughly half of which comes from methane, significantly larger than decarbonization alone over this timeframe."). *See also* Intergovernmental Panel on Climate Change (2022) *Summary for Policymakers*, *in* CLIMATE CHANGE 2022: MITIGATION OF CLIMATE CHANGE, *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Shukla P. R., Skea J., Slade R., Al Khourdajie A., van Diemen R., McCollum D., Pathak M., Some S., Vyas P., Fradera R., Belkacemi M., Hasija A., Lisboa G., Luz S., & Malley J. (eds.), 24 ("In modelled global low emission pathways, the projected reduction of cooling and warming aerosol emissions over time leads to net warming in the near- to mid-term. In these mitigation pathways, the projected reductions of cooling aerosols are mostly due to reduced fossil fuel combustion that was not equipped with effective air pollution controls."); Szopa S., Naik V., Adhikary B., Artaxo P., Berntsen T., Collins W. D., Fuzzi S., Gallardo L., Kiendler-Scharr A., Klimont Z., Liao H., Unger N., & Zanis P. (2021) *Chapter 6: Short-lived climate forcers*, in CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 8822 ("Additional CH_4 and BC mitigation would contribute to offsetting the additional warming associated with SO_2 reductions that would accompany decarbonization (*high confidence*)."); Ramanathan V. & Feng Y. (2008) *On avoiding dangerous anthropogenic interference with the climate system: Formidable challenges ahead*, PROC. NAT'L. ACAD. SCI. 105(38): 14245–14250, 14248 ("Switching from coal to ''cleaner'' natural gas will reduce CO_2 emission and thus would be effective in minimizing future increases in the committed warming. However, because it also reduces air pollution and thus the ABC [Atmospheric Brown Cloud] masking effect, it may speed up the approach to the committed warming of 2.4°C (1.4–4.3°C)."); United Nations Environment Programme & World Meteorological Organization (2011) INTEGRATED ASSESSMENT OF BLACK CARBON AND TROPOSPHERIC OZONE, 254 ("When all measures are fully implemented, warming during the 2030s relative to the present would be only half as much as in the reference scenario. In contrast, even a fairly aggressive strategy to reduce CO_2 emissions, as for the CO_2-measures scenario, does little to mitigate warming until after the next 20-30 years (Box 6.2). In fact, sulphur dioxide (SO_2) is coemitted with CO_2 in some of the most highly emitting activities, coal burning in large-scale combustion such as in power plants, for example, that are obvious targets for reduced usage under a CO_2-emissions mitigation strategy. Hence such strategies can lead to additional near-term warming (Figure 6.1), in a well-known temporary effect (e.g. Raes and Seinfeld, 2009), although most of the nearterm warming is driven by CO_2 emissions in the past."); *and* Shindell D., Sadavarte P., Aben I., Bredariol T. de O., Dreyfus G., Höglund-Isaksson L., Poulter B., Saunois M., Schmidt G. A., Szopa S., Rentz K., Parsons L., Qu Z., Faluvegi G., & Maasakkers J. D. (2024) *The methane imperative*, FRONT. SCI. 2: 1–28, 10 ("[S]uccessful reduction of CO_2 (and co-emissions) without simultaneous additional targeted methane reduction over this period would weakly affect long-term temperatures if methane reductions were achieved later (Figure 6A) but would lead to higher warming and substantially increased risk of overshooting warming thresholds over the next few decades.").

[69] Shindell D. & Smith C. J. (2019) *Climate and air-quality benefits of a realistic phase-out of fossil fuels*, NATURE 573: 408–411, 409–410, Addendum "Methods" ("These results differ greatly from the idealized picture of a near-instantaneous response to the removal of aerosol cooling followed by a slow transition to dominance by the effects of CO_2. In these more plausible cases, the temperature effects of the reduction in CO_2, SO_2 and CH_4 roughly balance one another until about 2035. After this, the cooling effects of reduced CO_2 continue to increase, whereas the warming induced by a reduction in SO_2 and the cooling induced by the reduction in CH_4 taper off, such that the cooling induced by the reduction in CO_2 dominates (Fig. 3). Examining the effects of CO_2 and SO_2 alone (Fig. 3d), the faster response of SO_2 to the changes in emissions means that the net effect of these two pollutants would indeed be a short-term warming—but a very small one, of between 0.02 °C and 0.10 °C in the ensemble mean temperature response (up to 0.30 °C for the 95th percentile across pathways). Accounting for all fossil-related emissions (Fig. 3e), any brief climate penalty decreases to no more than 0.05 °C (0.19 °C at the 95th percentile), with the smaller value largely due to the additional near-term cooling from reductions in methane. Nearly all the warming in the 2020s and 2030s (Fig. 2) is therefore attributable to the effect of the residual emissions (mainly of CO_2) during the gradual fossil phase-out, as well as the response to historical emissions. … We note that, although this study focuses on the effects of fossil-fuel related emissions, accounting for the effects of reductions in greenhouse gases from non-fossil sources—including fluorinated gases and both methane and nitrous oxide from agriculture—along with biofuels that are a large source of warming black carbon, could eliminate any near-term penalty entirely. In fact, given that the net effect of the fossil-fuel phase-out on temperature is minimal during the first 20 years (Fig. 3), reducing those other emissions is the only plausible way in which to decrease warming during that period."). *See also* Lelieveld J., Klingmüller K., Pozzer A., Burnett R. T., Haines A., & Ramanathan V. (2019) *Effects of fossil fuel and total anthropogenic emission removal on public health and climate*, PROC. NAT'L. ACAD. SCI. 116(15): 7192–7197, 7194 ("Some near-term mitigation can be achieved from the simultaneous reduction of short-lived greenhouse gases such as methane (CH_4), O_3, and hydrofluorocarbons (HFCs) (15, 23–25). Fossil-fuel-related CH_4 emissions constitute nearly 20% of the total source, and removing all anthropogenic CH_4 (nearly 60% of the source), in addition to anthropogenic O_3, would limit the near-term warming to 0.36(±0.06) °C. While the current climate forcing of HFCs is still small, it will be critical to prevent increases in the future, as they are potent greenhouse gases (26). Table 1 presents the unavoidable net warming from emission control measures that simultaneously affect aerosols and greenhouse gases, which have many sources in common. SI Appendix, Table S1 lists these results for all countries, including the uncertainty intervals."). *Compare* Xu Y. & Ramanathan V. (2017) *Well below 2 °C: Mitigation strategies for avoiding dangerous to catastrophic climate changes*, PROC. NAT'L. ACAD. SCI. 114(39): 10315–10323.

[70] Berwyn B. (15 September 2021) *The Rate of Global Warming During Next 25 Years Could Be Double What it Was in the Previous 50, a Renowned Climate Scientist Warns*, INSIDE CLIMATE NEWS ("James Hansen, a climate scientist who shook Washington when he told Congress 33 years ago that human emissions of greenhouse gases were cooking the planet, is now warning that he expects the rate of global warming to double in the next 20 years. While still warning that it is carbon dioxide and methane that are driving global warming, Hansen said that, in this case, warming is being accelerated by the decline of other industrial pollutants that they've cleaned from it…. In Hansen's latest warning, he said scientists are dangerously underestimating the climate impact of reducing sulfate aerosol pollution. 'Something is going on in addition to greenhouse warming,' Hansen wrote, noting that July's average global temperature soared to its second-highest reading on record even though the Pacific Ocean is in a cooling La Niña phase that temporarily dampens signs of warming. Between now and 2040, he wrote that he expects the climate's rate of warming to double in an 'acceleration that can be traced to aerosols.' That acceleration could lead to total warming of 2 degrees Celsius by 2040, the upper limit of the temperature range that countries in the Paris accord agreed was needed to prevent disastrous impacts from climate change. What's more, Hansen and other researchers said the processes leading to the acceleration are not adequately measured, and some of the tools needed to gauge them aren't even in place…. A doubling of the rate of global warming would put the planet in the fast lane of glacial melting, sea level rise and coral reef ecosystem die-offs, as well as escalating heatwaves, droughts and floods. But that future is not yet set in stone, said Michael Mann, a climate scientist at Penn State. He said Hansen's prediction appears inconsistent with the scientific literature assessed by the Intergovernmental Panel on Climate Change. The IPCC's latest report advises "that reductions of carbon emissions by 50 percent over the next decade and net-zero by 2100, along with a ramp-down in both aerosols and other short-term agents, including black carbon and other trace anthropogenic greenhouse gases, stabilizes warming well below 2 degrees Celsius," Mann said. But the IPCC report also highlighted that

declining aerosol pollution will speed warming. "The removal of air pollution, either through air quality measures or because combustion processes are phased out to get rid of CO_2, will result in an increase in the resulting rate of warming," said climate scientist and IPCC report author Joeri Rogelj, director of research at the Imperial College London's Grantham Institute. There's a fix for at least some of this short-term increase in the rate of warming, he said. "The only measures that can counteract this increased rate of warming over the next decades are methane reductions," Rogelj said. "I just want to highlight that methane reductions have always been part of the portfolio of greenhouse gas emissions reductions that are necessary to meet the goals of the Paris Agreement. This new evidence only further emphasizes this need.").

[71] Bodansky D. & Pomerance R. (2021) *Sustaining the Arctic in Order to Sustain the Global Climate System*, SUSTAINABILITY 13(19): 1–5, 3 ("Volcanic eruptions provide proof-of-concept that stratospheric aerosols cool the planet. The sulfur aerosols injected into the stratosphere by the eruption of Mount Pinatubo in 1991 cooled the planet by about 0.5 °C."). *See also* NASA Earth Observatory (2001) *Global Effects of Mount Pinatubo* ("Pinatubo injected about 15 million tons of sulfur dioxide into the stratosphere, where it reacted with water to form a hazy layer of aerosol particles composed primarily of sulfuric acid droplets. Over the course of the next two years strong stratospheric winds spread these aerosol particles around the globe.… In the case of Mount Pinatubo, the result was a measurable cooling of the Earth's surface for a period of almost two years. Because they scatter and absorb incoming sunlight, aerosol particles exert a cooling effect on the Earth's surface. The Pinatubo eruption increased aerosol optical depth in the stratosphere by a factor of 10 to 100 times normal levels measured prior to the eruption. ("Aerosol optical depth" is a measure of how much light airborne particles prevent from passing through a column of atmosphere.) Consequently, over the next 15 months, scientists measured a drop in the average global temperature of about 1 degree F (0.6 degrees C)."); *and* Dutton E. G. & Christy J. R. (1992) *Solar radiative forcing at selected locations and evidence for global lower tropospheric cooling following the eruptions of El Chichón and Pinatubo*, GEOPHYS. RES. LETT. 19(23): 2313–2316, 2313 ("By September 1992 the global and northern hemispheric lower tropospheric temperatures had decreased 0.5°C and 0.7°C, respectively compared to pre-Pinatubo levels.").

[72] Nair H. R. C. R., Budhavant K., Manoj M. R., Andersson A., Satheesh S. K., Ramanathan V., & Gustafsson Ö. (2023) *Aerosol demasking enhances climate warming over South Asia*, NPJ CLIM. ATMOS. SCI. 6: 1–8, 5 ("The 18% decrease in the columnar aerosol loading, revealed by the large-scale geophysical perturbation experiment resulting from the COVID-19 shutdown, led to an increase in radiative forcing by 1.4 W m^{-2} when averaged over SA for the springtime (Table 1). This is about three-fourths of the CO_2 induced radiative forcing of 1.8 W m^{-2} [2]. If this were to happen over wide scales, as we would expect from a 100% switchover from fossil fuels to zero-emission renewables, the net radiative heating would increase drastically. This estimate also provides an opportunity for testing IPCC model predictions against observation. The observations broadly support the IPCC model predictions that aerosols have a net cooling effect on climate, with the implication that reducing aerosol sources would lead to net warming[38], as here quantified by observations. The major surprise from the study is the magnitude of the COVID shutdown-induced increase in surface-reaching solar radiation, the surface brightening, of the order of 15–20 W m^{-2}. This surface brightening has major implications for the regional climate, especially the monsoonal circulation[39], atmospheric circulation[24,40], and precipitation over SA, and likely also for East Asia and all tropical regions.").

[73] Quaas J., *et al.* (2022) *Robust evidence for reversal of the trend in aerosol effective climate forcing*, ATMOS. CHEM. PHYS. 22(18): 12221–12239, 12231 ("In conclusion, there are clear, robust and consistent signals for net declining anthropogenic aerosol influence on climate in the period since 2000, i.e. the period, for which high-quality satellite retrievals of all relevant quantities are available. The regions in which aerosol emissions declined (in particular North America, Europe and East Asia) dominate over regions with increasing trends. …The overall climate-relevant signal is a decline in negative [aerosol effective radiative forcing] by about 0.1 to 0.3 W $m^{-2,}$ i.e. between 15 and 50% of the 0.6 W m^{-2} increase in CO_2 ERF (Forster et al., 2021) in the same time period. This signal will most likely continue in the future, increasing the urgency for strong measures on reducing greenhouse gas emissions (McKenna et al., 2021).").

[74] Hodnebrog Ø., Myhre G., Jouan C., Andrews T., Forster P. M., Jia H., Loeb N. G., Olivié D. J. L., Paynter D., Quaas J., Raghuraman S. P., & Schulz M. (2024) *Recent reductions in aerosol emissions have increased Earth's energy imbalance*, COMMUN. EARTH ENVIRON. 5(1): 1–9, 5 ("A main finding from our model results is that the forcing

due to aerosol emission reductions has led to an approximate doubling of the trend in EEI over the 2001–2019 period (Fig. 1a, b).").

[75] Yuan T., Song H., Oreopoulos L., Wood R., Bian H., Breen K., Chin M., Yu H., Barahona D., Meyer K., & Platnick S. (2024) *Abrupt reduction in shipping emission as an inadvertent geoengineering termination shock produces substantial radiative warming*, COMMUN. EARTH ENVIRON. 5(1): 1–8, 3 ("We compare the radiative forcing due to IMO2020 and its effect on radiative energy balance with observed changes in relevant quantities. The comparison does not prove causality but provides a context to assess the impact of IMO2020. The low cloud dimming forcing of 0.2 Wm^{-2} from the IMO2020 represents a strong temporary shock to the net planetary heat uptake (Fig. 5A) that has been increasing at a rate of ~0.05 Wm^{-2}/yr in measurements. The net planetary heat uptake has increased by 0.25 Wm^{-2} since 2020, making the 0.2 Wm^{-2} due to IMO2020 nearly 80% of the total increase. The long-term trend of CERES TOA net radiation is 0.46 Wm^{-2}/ decade while it changes to 0.67 Wm^{-2}/decade since IMO2020 took effect. The difference is 0.21Wm^{-2} that is consistent with our estimated forcing. However, the record since 2020 is too short to ascertain the impact of IMO2020 on the long-term trend of the energy balance given its large interannual variations."); *compare* Forster P. M., *et al.* (2024) *Indicators of Global Climate Change 2023: annual update of key indicators of the state of the climate system and human influence*, EARTH SYST. SCI. DATA 16(6): 2625–2658, 2633 ("Sulfur emissions from shipping have declined since 2020, weakening the aerosol ERF and adding around +0.1 W m−2 over 2020 to 2023 (Gettelman et al., 2024; see Sect. S4.2.2).").

[76] Iles C. E., Samset B. H., Sandstad M., Schuhen N., Wilcox L. J., & Lund M. T. (2024) *Strong regional trends in extreme weather over the next two decades under high- and low-emissions pathways*, NAT. GEOSCI. 17(9): 845–850, 849 ("While results are mixed, we do find that aerosol clean-up is associated with an enhanced increase in the warmest days in both summer and winter months over parts of southern and eastern Asia, accompanied by a winter (December–January–February) wetting (Supplementary Fig. 15). These results are consistent with the expected influence of a loss of regional, near-source aerosol-induced surface cooling. Effects on Asian summer monsoon precipitation were mixed, with two models (ACCESS-ESM1-5 and MPI-ESM1-2-LR) showing statistically significant enhanced monsoon season wet extreme rates."); S18 ("Here, we test this by examining the difference in near-term rates of change in SSP1-2.6 and SSP3-7.0, i.e. contrasting a socioeconomic scenario with strong air quality policies leading to a rapid clean-up of Asian aerosols (SSP1) with a scenario with continued high levels of aerosol emissions (SSP3). Over the period 2021-2040, SSP1-2.6 and SSP3-7.0 have only moderately different greenhouse gas concentration trends (reaching 458 ppm and 493 ppm of CO2 in 2040 respectively[25]; Figure S14), but marked differences in aerosol trends[26]. Hence, when comparing these scenarios, we can expect regional climate responses to have a strong aerosol-induced component, possibly compounded with the effects of land use change[27]. Figure S15 shows that, for both the boreal summer and winter months (JJA, DJF), we indeed see an enhanced increase in the warmest days in SSP1-2.6 over India and parts of China relative to SSP3-7.0, whilst in most other places SSP3- 7.0 warms more rapidly than SSP1-2.6. This enhanced TXx increase can be seen in three of the four models used and is statistically significant (K-S test, $p<0.05$). In the last model, CanESM5, the effect is present but is likely masked by a very strong warming response to the higher levels of greenhouse gases in SSP3-7.0, due to the high climate sensitivity of this model[28].").

[77] Szopa S., Naik V., Adhikary B., Artaxo P., Berntsen T., Collins W. D., Fuzzi S., Gallardo L., Kiendler-Scharr A., Klimont Z., Liao H., Unger N., & Zanis P. (2021) *Chapter 6: Short-lived climate forcers*, in CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 821, 822 ("Across the SSPs, the collective reduction of CH_4, ozone precursors and HFCs can make a difference of global mean surface air temperature of 0.2 with a very likely range of [0.1–0.4] °C in 2040 and 0.8 with a very likely range of [0.5–1.3] °C at the end of the 21st century (comparing SSP3-7.0 and SSP1-1.9), which is substantial in the context of the Paris Agreement. Sustained methane mitigation, wherever it occurs, stands out as an option that combines near- and long-term gains on surface temperature (*high confidence*) and leads to air quality benefits by reducing surface ozone levels globally (*high confidence*). … Additional CH_4 and BC mitigation would contribute to offsetting the additional warming associated with SO_2 reductions that would accompany decarbonization (*high confidence*).").

[78] Intergovernmental Panel on Climate Change (2023) AR6 SYNTHESIS REPORT: CLIMATE CHANGE 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K.,

Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 59 ("Mitigation actions will have other sustainable development co-benefits (*high confidence*). Mitigation will improve air quality and human health in the near-term notably because many air pollutants are co-emitted by GHG emitting sectors and because methane emissions leads to surface ozone formation (*high confidence*) The benefits from air quality improvement include prevention of air pollution-related premature deaths, chronic diseases and damages to ecosystems and crops. The economic benefits for human health from air quality improvement arising from mitigation action can be of the same order of magnitude as mitigation costs, and potentially even larger (*medium confidence*). As methane has a short lifetime but is a potent GHG, strong, rapid and sustained reductions in methane emissions can limit near-term warming and improve air quality by reducing global surface ozone (*high confidence*)."). *See also* Intergovernmental Panel on Climate Change (2023) *Summary for Policymakers*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 27 ("Strong, rapid and sustained reductions in CH_4 emissions would also limit the warming effect resulting from declining aerosol pollution and would improve air quality. (Figure SPM.10, Table SPM.2)").

[79] Shindell D. & Smith C. J. (2019) *Climate and air-quality benefits of a realistic phase-out of fossil fuels*, NATURE 573: 408–411, Addendum "Methods" ("We note that, although this study focuses on the effects of fossil-fuel related emissions, accounting for the effects of reductions in greenhouse gases from non-fossil sources—including fluorinated gases and both methane and nitrous oxide from agriculture—along with biofuels that are a large source of warming black carbon, could eliminate any near-term penalty entirely. In fact, given that the net effect of the fossil-fuel phase-out on temperature is minimal during the first 20 years (Fig. 3), reducing those other emissions is the only plausible way in which to decrease warming during that period."). *See also* United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS, 21 ("This is because a realistically paced phase-out of fossil fuels, or even a rapid one under aggressive decarbonization, is likely to have minimal net impacts on near-term temperatures due to the removal of co-emitted aerosols (Shindell and Smith 2019). As methane is the most powerful driver of climate change among the short-lived substances (Myhre et al. 2013), mitigation of methane emissions is very likely to be the most powerful lever in reducing near-term warming. This is consistent with other assessments; for example, the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5) showed that methane controls implemented between 2010 and 2030 would lead to a larger reduction in 2040 warming than the difference between RCPs 2.6, 4.5 and 6.0 scenarios. (The noted IPCC AR5-era scenarios are called representative concentration pathways (RCPs, with the numerical value indicating the target radiative forcing in 2100 (Kirtman et al. 2013))."); *and* Shindell D., Sadavarte P., Aben I., Bredariol T. de O., Dreyfus G., Höglund-Isaksson L., Poulter B., Saunois M., Schmidt G. A., Szopa S., Rentz K., Parsons L., Qu Z., Faluvegi G., & Maasakkers J. D. (2024) *The methane imperative*, FRONT. SCI. 2: 1–28, 9–10 ("Given the smaller role of other non-CO_2 climate pollutants, methane emission cuts therefore provide the strongest leverage for near-term warming reduction (Figure 5)(13, 95). Achievement of methane reductions consistent with the average in 1.5°C scenarios could reduce warming by ~0.3°C by 2050 in comparison with baseline increases (4). A hypothetical complete elimination of anthropogenic methane emissions could avert up to 1°C of warming by 2050 relative to the high emissions Shared Socioeconomic Pathway [SSP; (96)] SSP3–7.0 scenario (97). This large near-term impact partly reflects methane's short lifetime; >90% of increased atmospheric methane would be removed within 30 years of an abrupt cessation of anthropogenic emissions compared with only ~25% of increased CO_2 following CO_2 emission cessation (98).").

[80] Dreyfus G. B., Xu Y., Shindell D. T., Zaelke D., & Ramanathan V. (2022) *Mitigating climate disruption in time: A self-consistent approach for avoiding both near-term and long-term global warming*, PROC. NAT'L. ACAD. SCI. 119(22): 1–8, 5 ("By 2050, the net avoided warming from the targeted non-CO_2 measures is 0.26°C, almost 4 times larger than the net benefit of decarbonization alone (0.07°C) (Table S5).").

[81] 0.34 °C = 0.07 °C (from decarbonization) plus 0.26 °C (from measures targeting SLCPs), with rounding; *see* Dreyfus G. B., Xu Y., Shindell D. T., Zaelke D., & Ramanathan V. (2022) *Mitigating climate disruption in time: A self-consistent approach for avoiding both near-term and long-term global warming*, PROC. NAT'L. ACAD. SCI. 119(22): 1–8.

[82] Dreyfus G. B., Xu Y., Shindell D. T., Zaelke D., & Ramanathan V. (2022) *Mitigating climate disruption in time: A self-consistent approach for avoiding both near-term and long-term global warming*, PROC. NAT'L. ACAD. SCI. 119(22): 1–8, 5 ("Aggressive decarbonization to achieve net-zero CO_2 emissions in the 2050s (as in the decarb-only scenario) results in weakly accelerated net warming compared to the reference case, with a positive warming up to 0.03 °C in the mid-2030s, and no net avoided warming until the mid-2040s due to the reduction in co-emitted cooling aerosols (Figure 3a). By 2050, decarbonization measures result in very limited net avoided warming (0.07°C), consistent with Shindell and Smith, but rise to a likely detectable 0.25°C by 2060 and a major benefit of 1.4°C by 2100 (Table S5). In contrast, pairing decarbonization with mitigation measures targeting CH_4, BC, HFC, and N_2O (not an SLCP due to its longer lifetime) independent from decarbonization are essential to slowing the rate of warming by the 2030s to under 0.3°C per decade (Table 1, Figure 3b), similar to the 0.2°C to 0.25°C per decade warming prior to 2020. Recent studies suggest that rate of warming rather than level of warming controls likelihood of record-shattering extreme weather events. By 2050, the net avoided warming from the targeted non-CO_2 measures is 0.26°C, almost 4 times larger than the net benefit of decarbonization alone (0.07°C) (Table S5).").

[83] McKenna C. M., Maycock A. C., Forster P. M., Smith C. J., & Tokarska K. B. (2021) *Stringent mitigation substantially reduces risk of unprecedented near-term warming rates*, NAT. CLIM. CHANG. 11(2): 126–131, 126 ("Here we use observationally constrained projections from the latest comprehensive climate models and a simple climate model emulator to show that pursuing stringent mitigation consistent with holding long-term warming below 1.5 °C reduces the risk of unprecedented warming rates in the next 20 years by a factor of 13 compared with a no mitigation scenario, even after accounting for internal variability. Therefore, in addition to long-term benefits, stringent mitigation offers substantial near-term benefits by offering societies and ecosystems a greater chance to adapt to and avoid the worst climate change impacts." [Mitigation scenarios showing reductions to CO_2, CH_4, N_2O, BC, and SO_2 shown in Supplementary Figure 3.]).

[84] Liang Q., Rigby M., Fang X., Godwin D., Mühle J., Saito T., Stanley K. M., Velders G. J. M., Bernath P., Derek N., Reimann S., Simpson I. J., & Western L. (2022) *Chapter 2: Hydrofluorocarbons (HFCs)*, *in* SCIENTIFIC ASSESSMENT OF OZONE DEPLETION: 2022, Global Ozone Research and Monitoring Project–Report No. 278, World Meteorological Organization, United Nations Environment Programme, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, & European Commission, 145 (Figure 2-18 shows warming absent control measures on the order of 0.12°C compared with the updated Kigali scenario showing a warming of about 0.05°C). *See also* Szopa S., Naik V., Adhikary B., Artaxo P., Berntsen T., Collins W. D., Fuzzi S., Gallardo L., Kiendler-Scharr A., Klimont Z., Liao H., Unger N., & Zanis P. (2021) *Chapter 6: Short-lived Climate Forcers*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 873 ("Efficient implementation of the Kigali Amendment and national and regional regulations has been projected to reduce global average warming in 2050 by 0.05°C–0.07°C (Klimont et al., 2017b; WMO, 2018) and by 0.2°C–0.4°C in 2100 compared with the baseline (see Figure 2.20 of WMO, 2018). Analysis of SSP scenarios based on an emulator (Section 6.7.3) shows a comparable mitigation potential of about 0.02°C–0.07°C in 2050 and about 0.1°C–0.3°C in 2100 (Figure 6.22, SSP5-8.5 versus SSP1-2.6). Furthermore, the energy efficiency improvements of cooling equipment alongside the transition to low-global-warming potential alternative refrigerants for refrigeration and air-conditioning equipment could potentially increase the climate benefits from the HFC phasedown under the Kigali Amendment (Shah et al., 2015; Höglund-Isaksson et al., 2017; Purohit and Höglund-Isaksson, 2017; WMO, 2018). Purohit et al. (2020) estimated that depending on the expected rate of technological development, improving the energy efficiency of stationary cooling technologies and compliance with the Kigali Amendment could bring future global electricity savings of more than 20% of the world's expected electricity consumption beyond 2050 or cumulative reduction of about 75–275 Gt CO_2-eq over the period 2018–2100 (medium confidence). This could potentially double the climate benefits of the HFC phase-down of the Kigali Amendment as well as result in small air-quality improvements due to reduced air pollutant emissions from the power sector (i.e., 8–16% reduction of $PM_{2.5}$, SO_2 and NO_x; Purohit et al., 2020).").

[85] Su X., Shiogama H., Tanaka K., Tachiiri K., Hajima T., Watanabe M., Kawamiya M., Takahashi K., & Yokohata T. (2024) *Reductions in atmospheric levels of non-CO_2 greenhouse gases explain about a quarter of the 1998-2012 warming slowdown*, COMMUN. EARTH ENVIRON. 5(1): 1–11, 1 ("The observed global mean surface temperature

increase from 1998 to 2012 was slower than that since 1951. The relative contributions of all relevant factors including climate forcers, however, have not been comprehensively analyzed. Using a reduced-complexity climate model and an observationally constrained statistical model, here we find that La Niña cooling and a descending solar cycle contributed approximately 50% and 26% of the total warming slowdown during 1998-2012 compared to 1951-2012. Furthermore, reduced ozone-depleting substances and methane accounted for roughly a quarter of the total warming slowdown, which can be explained by changes in atmospheric concentrations. We identify that non-CO_2 greenhouse gases played an important role in slowing global warming during 1998-2012."); 4 ("Growth in methane ΔC is reported to have slowed from the 1980s and to have stabilized between 1999 and 2006[42–47], owing to the notable methane reductions in the agriculture sector in Europe and Russia, as well as in the energy sector in Europe, Japan, the Middle East and Russia, before or during the warming slowdown period. These reductions may, in part, offset the rapid growth in methane emissions in China and India (Supplementary Fig. 8)[48,49].").

[86] Ripple W. J., Wolf C., Newsome T. M., Barnard P., & Moomaw W. R. (2020) *World Scientists' Warning of a Climate Emergency*, BIOSCI. 70: 8–12, 11 ("We need to promptly reduce the emissions of short-lived climate pollutants, including methane (figure 2b), black carbon (soot), and hydrofluorocarbons (HFCs). Doing this could slow climate feedback loops and potentially reduce the short-term warming trend by more than 50% over the next few decades while saving millions of lives and increasing crop yields due to reduced air pollution (Shindell et al. 2017). The 2016 Kigali amendment to phase down HFCs is welcomed.").

[87] Ripple W. J., Wolf C., Gregg J. W., Rockström J., Mann M. E., Oreskes N., Lenton T. M., Rahmstorf S., Newsome T. M., Xu C., Svenning J.-C., Pereira C. C., Law B. E., & Crowther T. W. (2024) *The 2024 state of the climate report: Perilous times on planet Earth*, BIOSCI.: 1–13, 11 ("In addition, pricing and reducing methane emissions is critical for effectively mitigating climate change. Methane is a potent greenhouse gas, and unlike carbon dioxide, which persists in the atmosphere for centuries, methane has a relatively short atmospheric lifetime,making reductions impactful in the short term (Shindell et al. 2024). Drastically cutting methane emissions can slow the near-term rate of global warming, helping to avoid tipping points and extreme climate impacts."). *See also* Ripple W. J., Wolf C., Newsome T. M., Gregg J. W., Lenton T. M., Palomo I., Eikelboom J. A. J., Law B. E., Huq S., Duffy P. B., & Rockström J. (2021) *World Scientists' Warning of a Climate Emergency 2021*, BIOSCI. 71(9): 894–898, 897 ("Given the impacts we are seeing at roughly 1.25 degrees Celsius (°C) warming, combined with the many reinforcing feedback loops and potential tipping points, massive-scale climate action is urgently needed. The remaining carbon budget for 1.5°C was recently estimated to have a 17% chance of being negative, indicating that we may already have lost the opportunity to limit warming to this level without overshoot or risky geoengineering (Matthews et al. 2021). Because of the limited time available, priorities must shift toward immediate and drastic reductions in dangerous short-lived greenhouse gases, especially methane (UNEP/CCAC 2021).").

[88] Milkoreit M. (ed.) (2023) *Section 3: Governance of Earth system tipping points*, in GLOBAL TIPPING POINTS REPORT 2023, Lenton T. M., *et al.* (eds.), 26 ("Outside of the UNFCCC, intergovernmental efforts to manage SLCPs are an important dimension of global climate mitigation efforts, especially because they can have short-term benefits. SLCPs, including methane, tropospheric ozone and black carbon, can have disproportionate regional impacts on particular tipping systems. For example, black carbon deposition is particularly effective at melting snow and ice. Hence the mitigation of specific SLCPs can have a disproportionate benefit in preventing specific ESTPs. Mitigating SLCPs can also contribute to limiting global warming pressure on most ESTPs. According to IPCC AR6 WG1, across the Shared Socioeconomic Pathway climate scenarios, "the collective reduction of methane, ozone precursors, and hydrofluorocarbons (HFCs) can make a difference of 0.2°C with a very likely range of [0.1 to 0.4]°C in 2040 and 0.8°C with a very likely range of [0.5 to 1.3]°C at the end of the 21st Century". … In 2016, the Montreal Protocol on Substances that Deplete the Ozone Layer was complemented with the Kigali Amendment on the phaseout of HFCs. Further, under the Paris Agreement, some countries have included SLCP mitigation targets or policies in their NDCs, and various global cooperation efforts, including the Global Methane Pledge (Sun et al., 2021), have been launched to address methane emissions. Elevated action on SLCPs is essential because the effects are felt more rapidly than those of CO_2 abatement.")

[89] Möller T., Högner A., Schleussner C.-F., Bien S., Kitzmann N., Lamboll R., Rogelj J., Donges J., Rockström J., & Wunderling N. (2024) *Achieving net zero greenhouse gas emissions critical to limit climate tipping risks*, NAT.

COMMUN. 15(1): 1–11, 6 ("We find that tipping risk increases with every 0.1 °C of overshoot peak temperature. Further, we find a non-linear acceleration in tipping risk for peak overshoot temperatures above 2.0 °C resulting in more than 3% tipping risk increase per additional 0.1 °C peak temperature for overshoot temperatures exceeding 2.5 °C peak warming. This underscores the importance of the Paris Agreement climate objective[24] to hold warming to 'well below 2 °C' even in case of a temporary overshoot above 1.5 °C.").

[90] Möller T., Högner A., Schleussner C.-F., Bien S., Kitzmann N., Lamboll R., Rogelj J., Donges J., Rockström J., & Wunderling N. (2024) *Achieving net zero greenhouse gas emissions critical to limit climate tipping risks*, NAT. COMMUN. 15(1): 1–11, 3 ("We find that tipping risks until 2300 are substantial for several of the assessed scenarios (see Fig. 3a, b). … If warming is returned to below 1.5 °C by 2100 after a high overshoot (median peak temperature exceeds 1.5 °C by more than 0.1 °C), tipping risks remain at or below 10% (median 2%; Neg-OS-0C and Neg-NZGHG). Failing to return warming below 1.5 °C by 2100, despite reaching NZGHG in this time, results in tipping risks of 0–24% (median 4%; GS-NZGHG). This confirms that the risks of overshoot can be minimised if warming is swiftly reversed. However, this would require rapid employment of appropriate mitigation measures.").

[91] Möller T., Högner A., Schleussner C.-F., Bien S., Kitzmann N., Lamboll R., Rogelj J., Donges J., Rockström J., & Wunderling N. (2024) *Achieving net zero greenhouse gas emissions critical to limit climate tipping risks*, NAT. COMMUN. 15(1): 1–11, 8 ("We classify the scenarios into three groups according to whether they achieve NZGHG emissions by 2100—as set out in the Paris Agreement Article 4.1—or not, and whether they maintain NZGHG in the long term: (i) 'No-NZGHG', (ii) 'No-long-term-NZGHG', and (iii) 'NZGHG' scenarios. NZGHG is understood here as achieving net zero Kyoto GHG emissions, i.e. CO_2, CH_4, N_2O, SF_6, HFC, and PFC emissions, as aggregated with the GWP100 metric[36].").

[92] Riahi K., *et al.* (2022) *Chapter 3: Mitigation Pathways Compatible with Long-term Goals*, in CLIMATE CHANGE 2022: MITIGATION OF CLIMATE CHANGE, Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Shukla, P. R. et al. (eds.) Table 3.1 ("C1: Limit warming to 1.5°C (>50%) with no or limited overshoot: Reach or exceed 1.5°C during the 21st century with a likelihood of ≤67%, and limit warming to 1.5°C in 2100 with a likelihood >50%. Limited overshoot refers to exceeding 1.5°C by up to about 0.1°C and for up to several decades.").

[93] Geden O. & Löschel A. (2017) *Define limits for temperature overshoot targets*, NAT. GEOSCI. 10(12): 881–882, 881 ("Specifically, the Paris Agreement does not contain any wording on temporary temperature overshoot, or on its maximum duration or magnitude. Nor does it provide a target time by which warming must be brought back below 1.5 °C, which is a key constraint in terms of achieving accountability.").

[94] Reisinger A. & Geden O. (2023) *Temporary overshoot: Origins, prospects, and a long path ahead*, ONE EARTH 6(12): 1631–1637, 1633 ("The distinction between pathways with ''limited'' and ''high'' temperature overshoot, introduced in the SR15 and continued in the 6th Assessment Report, provides some dimensions to describe overshoot in terms relevant to climate-related risks. One dimension is the magnitude of exceedance above a specified temperature limit, ranging from less than one-tenth to several tenths of a degree above 1.5 °C in pathways assessed by the IPCC that still return below 1.5 °C before 2100. A more complex dimension would take not only the magnitude but also duration of exceedance into account, representing the integral under the temporary exceedance and expressed in degree-years, which range from less than 1-to about 10-years as best estimate in those same pathways. These physical metrics could be useful insofar as some impacts scale largely with excess temperature (e.g., heat-related morbidity and mortality), while others are related more to excess cumulative warming (e.g., sea level rise due to thermal expansion of ocean water), and temperature serving as proxy for various climatic impact drivers. However, while those metrics may be useful and are being used in literature on climate-related impacts and risks in the context of rising temperature, they are unlikely to do justice to the diversity of impacts and risks under overshoot trajectories.").

[95] Reisinger A. & Geden O. (2023) *Temporary overshoot: Origins, prospects, and a long path ahead*, ONE EARTH 6(12): 1631–1637, 1634 ("One simple reason is irreversibility: the extinction of species is a key concern under higher warming levels, but bringing warming back down again will not reverse such extinctions, even though the risk to surviving species would be reduced. Similar issues apply to near irreversibility of the loss of ice sheets and glaciers

or rather the need for temperature to fall far below current levels for those ice masses to build up again. A related but more complex reason is that impacts, once manifested, leave behind an altered world that cannot be reversed by declining global warming levels…. At best, many human and natural systems will exhibit a significant hysteresis in their recovery after global warming levels decline again, but often they will assume a permanently altered state that is difficult to return to the original condition. A related issue is the risk represented by tipping points, understood by the IPCC to be ''critical thresholds beyond which a system reorganizes, often abruptly and/or irreversibly….If a tipping point is reached during the overshoot period, the consequences would generally not be reversible.").

[96] Möller T., Högner A., Schleussner C.-F., Bien S., Kitzmann N., Lamboll R., Rogelj J., Donges J., Rockström J., & Wunderling N. (2024) *Achieving net zero greenhouse gas emissions critical to limit climate tipping risks*, NAT. COMMUN. 15(1): 1–11, 3 ("In the medium term the two faster tipping elements, AMOC (tipping time: 15–300 years) and AMAZ (tipping time: 50–200 years) display the highest risks while tipping remains below 11% for the two slow-onset tipping elements, GIS (tipping time: 1000–15,000 years) and WAIS (tipping time: 500–13,000 years). In the long term, risks are highest for AMOC and WAIS."); 7 ("While we assess the probabilities of at least one element tipping on the basis of mitigation behaviour until 2300, the implications of overshooting 1.5 °C will unfold over millennia[15]. For example, Global Mean Sea Level will continue to rise for up to 10,000 years or more after emissions have reached NZGHG, due to the slow response of the ice sheets of Greenland and Antarctica[15]. The Global Mean Sea Level Rise (GMSLR) by 2300, committed from historic and currently pledged emissions until 2030, already amounts to 0.8–1.4 m[48]. Exceeding 1.5 °C may lead to a commitment of at least 2–3 m GMSLR on a timescale of 2000 years, and 6–7 m commitment on a 10,000-year timescale[15].").

[97] Schleussner C.-F., *et al.* (2024) *Overconfidence in climate overshoot*, NATURE 634(8033): 366–373, 369 ("In the NorESM2-LM model, we observe a reversal of regional temperature scaling with Global mean surface air temperature (GMST) change for the North Atlantic and adjacent European land regions under overshoot (Fig. 3c), leading to a temporary regional cooling and subsequent regional recovery and warming[32] (Fig. 3e). The pattern in which the North Atlantic cools regionally despite planetary warming is also present in the stabilization scenario but is less pronounced. In the GFDL-ESM2M model, the imprint of overshoot and stabilization on regional climate is less pronounced. But temperature changes associated with a time-lagged AMOC recovery about 100 years after peak warming and to higher levels than in the stabilization scenario are also evident (Fig. 3d,f). We note that these simulations do not include increased Greenland meltwater influx that may suppress a potential AMOC recovery under overshoot[33]. Similarly pronounced features emerge for precipitation in both models, in particular, related to movements of the Inter-Tropical Convergence Zone in response to changes in the AMOC4 (Extended Data Fig. 5). Multi-model transient overshoot simulations further corroborate the finding that AMOC dynamics and related changes in regional climate are a dominant feature of overshoot pathways[5,32] (Methods and Extended Data Figs. 7 and 8). They also indicate a continuous warming of the Southern Ocean relative to the rest of the globe as a result of fast and slow response patterns, and changes in regional climate following reduced aerosol loadings (in particular in South and East Asia)[18]. Taken together, our results suggest that regional climate changes cannot be approximated well by GMST after peak warming.").

[98] Reisinger A. & Geden O. (2023) *Temporary overshoot: Origins, prospects, and a long path ahead*, ONE EARTH 6(12): 1631–1637, 1631 ("A subsequent decline in global warming relies on sustained net-negative CO_2 emissions from human activities, with total removals outweighing residual emissions of all long-lived greenhouse gases. *See also* Zickfeld K., MacIsaac A. J., Canadell J. G., Fuss S., Jackson R. B., Jones C. D., Lohila A., Matthews H. D., Peters G. P., Rogelj J., & Zaehle S. (2023) *Net-zero approaches must consider Earth system impacts to achieve climate goals*, NAT. CLIM. CHANG. 13(12): 1298–1305, 1303 ("However, CO_2 emissions and removals are not equivalent in terms of their effects on climate, and rigorous and comprehensive quantification of the full climate effects of CDR is crucial to ensuring that balancing CO2 emissions and removals will be successful in stabilizing warming. This is particularly important when CDR is implemented to balance fossil fuel emissions, as neglecting non-CO_2 effects could cause additional warming and result in environmental and societal harm. … Even with continued scientific advances, many remaining uncertainties about the climate effects of CDR are unlikely to be fully resolved in the short timeframe available to design and implement climate policies consistent with the Paris Agreement climate goals. This constraint further underscores the need to prioritize reducing emissions as rapidly and as much as possible."); *and* Schleussner C.-F., *et al.* (2024) *Overconfidence in climate overshoot*, NATURE 634(8033): 366–373, 368 ("Upscaling of CDR may

be constrained considerably[9] by factors such as lack of policy support and business models, technological uncertainty and public opposition (for example, perceived risks of delaying mitigation[25]). Even if technical removal potentials prove to be large, sustainability and equity considerations would limit acceptable deployment scales[8,9]. Insufficient technological readiness may be an important bottleneck, as current removal rates from CDR methods other than afforestation and reforestation are minuscule (about 2 Mt CO_2 yr^{-1})[26] and would require a more than 1,000-fold increase by 2050 (ref. 27). Beyond technological concerns, an array of unintended or uncertain permanence issues and system feedback (Extended Data Table 2) might reduce or offset the contribution of CDR to mitigation[26,28].").

[99] Schleussner C.-F., *et al.* (2024) *Overconfidence in climate overshoot*, NATURE 634(8033): 366–373, 372 ("First, emissions reductions need to be accelerated as quickly as possible to slow down temperature increase and reduce peak warming. Pursuing such an enhanced protection pathway (Table 1) is the only robust strategy to, if not avoid then, at least minimize, far-reaching climate risks over the twenty-first century.").

[100] Reisinger A. & Geden O. (2023) *Temporary overshoot: Origins, prospects, and a long path ahead*, ONE EARTH 6(12): 1631–1637, 1635 ("A third factor is the contribution from short-lived non-CO2 emissions, especially methane. For short-lived climate forcers, their contribution to global warming depends mostly on their rate of emissions. Reducing methane emissions not only in the near term but even further beyond mid-century thus offers an additional lever to reduce warming levels below the peak.").

[101] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS, 17 ("Mitigation of methane is very likely the strategy with the greatest potential to decrease warming over the next 20 years."). *See also* Ross K., Waskow D., & Ge M. (17 September 2021) *How Methane Emissions Contribute to Climate Change*, WORLD RESOURCES INSTITUTE ("Methane is the second most abundant human-caused greenhouse gas (GHG), and is 86 times more powerful than carbon dioxide over 20 years in the atmosphere (34 times more powerful over 100 years). Because it exists for a relatively short time in the atmosphere, cutting methane provides a quick benefit in terms of limiting near-term temperature rise. Studies estimate that ambitious actions to reduce methane can avoid 0.3 degrees C of warming by 2050.").; *and* Intergovernmental Panel on Climate Change (2023) AR6 SYNTHESIS REPORT: CLIMATE CHANGE 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 33, 57 ("Global warming will continue to increase in the near term in nearly all considered scenarios and modelled pathways. Deep, rapid and sustained GHG emissions reductions, reaching net zero CO_2 emissions and including strong emissions reductions of other GHGs, in particular CH_4, are necessary to limit warming to 1.5°C (>50%) or less than 2°C (>67%) by the end of century (*high confidence*). … All global modelled pathways that limit warming to 2°C (>67%) or lower by 2100 involve reductions in both net CO_2 emissions and non-CO_2 emissions (see Figure 3.6) (*high confidence*). For example, in pathways that limit warming to 1.5°C (>50%) with no or limited overshoot, global CH_4 (methane) emissions are reduced by 34% [21–57%] below 2019 levels by 2030 and by 44% [31–63%] in 2040 (*high confidence*). Global CH_4 emissions are reduced by 24% [9–53%] below 2019 levels by 2030 and by 37% [20–60%] in 2040 in modelled pathways that limit warming to 2°C with action starting in 2020 (>67%) (*high confidence*). (CrossSection Box.2).").

[102] Ripple W. J., Wolf C., Gregg J. W., Rockström J., Mann M. E., Oreskes N., Lenton T. M., Rahmstorf S., Newsome T. M., Xu C., Svenning J.-C., Pereira C. C., Law B. E., & Crowther T. W. (2024) *The 2024 state of the climate report: Perilous times on planet Earth*, BIOSCI.: 1–13, 10 ("In addition [to cutting CO_2], pricing and reducing methane emissions is critical for effectively mitigating climate change. Methane is a potent greenhouse gas, and unlike carbon dioxide, which persists in the atmosphere for centuries, methane has a relatively short atmospheric lifetime, making reductions impactful in the short term (Shindell et al. 2024). Drastically cutting methane emissions can slow the near-term rate of global warming, helping to avoid tipping points and extreme climate impacts.").

[103] United Nations Environment Programme & Climate & Clean Air Coalition (2022) GLOBAL METHANE ASSESSMENT: 2030 BASELINE REPORT, 5 ("The Intergovernmental Panel on Climate Change (IPCC)'s Sixth Assessment shows that human-driven methane emissions are responsible for nearly 45 per cent of current net warming.

The IPCC has continuously emphasized the critical urgency of reducing anthropogenic emissions – from methane and from other climate pollutants – if the world is to stay below 1.5° and 2°C targets.").

[104] Intergovernmental Panel on Climate Change (2021) *Summary for Policymakers*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), Figure SPM.2.

[105] Rates of increase for methane for the 2020–2022 (15.2 ppb/yr) period were nearly double that of the 2011–2020 average (8.5 ppb/year), the fastest rates of increase since records started in 1983. However, the rate of increase was not as high for 2023 (+8.5 pbb) and 2024 (+9.5 ppb). *See* United States Department of Commerce, *Global Monitoring Laboratory - Carbon Cycle Greenhouse Gases* (*last visited* 22 April 2025).

[106] National Oceanic and Atmospheric Administration (5 April 2024) *No sign of greenhouse gases increases slowing in 2023* ("Methane levels in the atmosphere are now more than 160% higher than their pre-industrial level.").

[107] Ocko I. (4 December 2023) *Methane in the spotlight: 10 scientific facts you should know*, ENVIRONMENTAL DEFENSE FUND ("This year's methane emissions from human activities will cause around the same amount of warming over the next 10 years as this year's carbon dioxide emissions from burning fossil fuels.
Assumptions:
- Present-day methane emissions: 375 million metric tons (Saunois et al. 2020, Minx et al. 2021)
- Present-day carbon dioxide emissions from fossil fuel combustion: 35 billion metric tons (Friedlingstein et al., 2022)
- Methane Global Warming Potential (GWP) with 10-year time horizon: 100 (Equations in IPCC AR6 WGI 2021)

Calculation:
Methane CO_2eq-10 = 375*100 = 37500 million metric tons = 37.5 billion metric tons ≈ 35 billion metric tons").

[108] Mar K. A., Unger C., Walderdorff L., & Butler T. (2022) *Beyond* CO_2 *equivalence: The impacts of methane on climate, ecosystems, and health*, ENV. SCI. POL. 134: 127–136, 128–129 ("Methane is a GHG and thereby a direct climate forcer; that is, it absorbs and re-radiates thermal radiation, contributing directly to the greenhouse effect. Unlike CO_2, CH_4 is chemically active, with atmospheric oxidation accounting for approximately 95% of its loss. Among other things, reactions of CH_4 lead to the production of tropospheric O_3 and stratospheric water vapor, and the end product of CH_4 oxidation is CO_2 itself (Forster et al., 2021). In this way, CH_4 also acts as an indirect climate forcer because it leads to the production of other GHGs (Fig. 1). A quantitative overview of radiative forcing due to CH_4 and its associated photochemical products is provided in Table 1. The chemical reactions of CH_4 also alter the atmospheric concentration of oxidants, especially the OH radical. This in turn has an indirect effect on the abundance of other trace gases and aerosols in the troposphere. In particular, increased atmospheric CH_4 provides an increased sink for OH [hydroxy radical], reducing the formation of sulfate aerosol (via SO_2 +OH). Since sulfate aerosol has a cooling effect on the climate (see also (Fig. 2) its reduction can be seen as an additional, indirect positive radiative forcing attributable to CH_4 (Shindell et al., 2009) calculate that this effect is equivalent to a radiative forcing of approximately + 0.1 W m^{-2} (Table 1), comparable to the CH_4-induced radiative forcing due to stratospheric water vapor.").

[109] Jackson R. B., Saunois M., Martinez A., Canadell J. G., Yu X., Li M., Poulter B., Raymond P. A., Regnier P., Ciais P., Davis S. J., & Patra P. K. (2024) *Human activities now fuel two-thirds of global methane emissions*, ENVIRON. RES. LETT. 19(10): 1–11, 2–5 ("Our best estimates for anthropogenic methane emissions in 2020, the last year for which full data for the GMB are available, are 372 [345–409] and 392 [368–409] Tg CH_4 yr^{-1} for BU and TD methods, respectively (figure 1, table 1). The largest emissions sources are: wetland and inland freshwaters, agriculture and waste, and fossil fuel production and use (figure 1). Direct anthropogenic emissions from TD estimates now comprise ∼65% of global emissions. When the ∼50 yr^{-1} or more of 'indirect anthropogenic emissions,' such as those from dams and reservoirs, are included (Saunois et al 2024), the total is more than two-thirds anthropogenic."). *See also* Saunois M., *et al.* (2024) *Global Methane Budget 2000–2020*, EARTH SYST. SCI. DATA DISCUSSIONS (*preprint*).

[110] Jackson R. B., Saunois M., Martinez A., Canadell J. G., Yu X., Li M., Poulter B., Raymond P. A., Regnier P., Ciais P., Davis S. J., & Patra P. K. (2024) *Human activities now fuel two-thirds of global methane emissions*, ENVIRON.

RES. LETT. 19(10): 1–11, 5 ("One major change from previous Global Methane Budgets is the allocation of some freshwater and wetland emissions to anthropogenic actions, such as emissions from human-built reservoirs (Saunois et al 2024). For example, 50% of inland water emissions (56 of 112 Tg yr^{-1}) are now estimated to be influenced by anthropogenic actions, including those from human-built reservoirs (30 Tg yr^{-1}) and through eutrophication, warming, and other anthropogenically driven factors (Saunois et al 2024). Similarly, 30 Tg yr^{-1} of the ∼160 Tg yr^{-1} emitted from wetlands globally (table 1) are estimated to be influenced by anthropogenic factors such as climate change and CO2 fertilization. Given this new partitioning of previously categorized 'natural' wetland and inland freshwater emissions, the contribution of 'anthropogenic methane emissions' is likely to be greater than two-thirds, even when including only the additional 30 Tg yr^{-1} of emissions from human-built reservoirs.").

[111] Jackson R. B., Saunois M., Martinez A., Canadell J. G., Yu X., Li M., Poulter B., Raymond P. A., Regnier P., Ciais P., Davis S. J., & Patra P. K. (2024) *Human activities now fuel two-thirds of global methane emissions*, ENVIRON. RES. LETT. 19(10): 1–11, 2 ("Estimated methane emissions from inland freshwaters for the new global methane budget use new spatial products and for the first time attribute some freshwater sources to anthropogenic activities ('direct' via river damming or other human-constructed small lakes and ponds) or influences ('indirect' via eutrophication induced by enhanced nutrient loadings from the surrounding catchments).").

[112] United Nations Environment Programme (2021) EMISSIONS GAP REPORT 2021: THE HEAT IS ON – A WORLD OF CLIMATE PROMISES NOT YET DELIVERED, 47 ("Over the last two decades, the main cause of increasing atmospheric methane is likely increasing anthropogenic emissions, with hotspot contributions from agriculture and waste in South and South-East Asia, South America and Africa, and from fossil fuels in China, the Russian Federation and the United States of America (Jackson *et al.* 2020). Emissions from natural sources may also be increasing, as wetlands warm, tropical rainfall increases and permafrost thaws.").

[113] Rates of increase for methane for the 2020–2022 (15.2 ppb/yr) period were nearly double that of the 2011–2020 average (8.5 ppb/year), the fastest rates of increase since records started in 1983. However, the rate of increase was not as high for 2023 (+8.5 pbb) and 2024 (+9.5 ppb). *See* United States Department of Commerce, *Global Monitoring Laboratory - Carbon Cycle Greenhouse Gases* (*last visited* 22 April 2025).

[114] Nisbet E. G. (2023) *Slaying the methane minotaur*, PROC. NAT'L. ACAD. SCI. 120(49): 1–3, 1 ("Despite atmospheric methane's significance in driving climate change, the global methane budget is still poorly constrained (1–4). Neither sources nor sinks are accurately quantified, and the rapid year-on-year changes remain poorly understood (5). It is difficult to determine how much methane is from natural microbial sources, how much from human agriculture and waste, and how much from fossil fuel use and natural geological sources."). *See also* Lan X., Nisbet E. G., Dlugokencky E. J., & Michel S. E. (2021) *What do we know about the global methane budget? Results from four decades of atmospheric CH_4 observations and the way forward*, PHIL. TRANS. R. SOC. A 379(2210): 1–14, 11 ("Explaining the renewed and accelerating increase in atmospheric CH_4 burden since 2007 remains challenging, and the exact causes are not yet clear. But, the observations we describe suggest that increased emissions from microbial sources are the strongest driver, with a relatively smaller contribution from other processes, e.g., fossil fuel exploitation. A more difficult question to answer is the one posed by this special issue: is warming feeding the warming? We cannot say for certain, but we cannot rule out the possibility that climate change is increasing CH_4 emissions. The strong signals from the tropics combined with the isotopic data are consistent with increased emissions from natural wetlands, but large [interannual variability (IAV)] and inter-decadal variability in wetland drivers like precipitation make it difficult to identify small trends. Observations are needed that will help process models capture this variability. The size of the IAV illustrates the potential scope of uncontrollable near-future change and emphasizes the urgency of reducing the global methane burden by mitigating the methane emissions that we can control, from the fossil fuel and agricultural sectors."). *Compare* Gauci V., Pangala S. R., Shenkin A., Barba J., Bastviken D., Figueiredo V., Gomez C., Enrich-Prast A., Sayer E., Stauffer T., Welch B., Elias D., McNamara N., Allen M., & Malhi Y. (2024) *Global atmospheric methane uptake by upland tree woody surfaces*, NATURE 631(8022): 796–800, 796 ("Stable carbon isotope measurement of methane in woody surface chamber air and process-level investigations on extracted wood cores are consistent with methanotrophy, suggesting a microbially mediated drawdown of methane on and in tree woody surfaces and tissues. By applying terrestrial laser scanning-derived allometry to quantify global forest tree woody surface area, a preliminary first estimate suggests that trees may contribute 24.6–49.9 Tg of

atmospheric methane uptake globally. Our findings indicate that the climate benefits of tropical and temperate forest protection and reforestation may be greater than previously assumed.”).

[115] Shindell D., Sadavarte P., Aben I., Bredariol T. de O., Dreyfus G., Höglund-Isaksson L., Poulter B., Saunois M., Schmidt G. A., Szopa S., Rentz K., Parsons L., Qu Z., Faluvegi G., & Maasakkers J. D. (2024) *The methane imperative*, FRONT. SCI. 2: 1–28, 5 (“A switch from La Niña to El Niño during 2023 appears to have reduced the observed growth rate (Figure 2), supporting a large role for wetland responses to La Niña in the very high 2020–2022 growth rates. However, emissions appear to have remained substantially higher in 2023 relative to pre-2020 values (Figure 1B), suggesting longer-term contributions from increasing anthropogenic sources along with a forced trend in natural sources. Recent work also suggests a potentially permanent shift to an altered state of enhanced wetland methane emissions (8).”). *See also* Qu Z., Jacob D. J., Bloom A. A., Worden J. R., Parker R. J., & Boesch H. (2024) *Inverse modeling of 2010–2022 satellite observations shows that inundation of the wet tropics drove the 2020–2022 methane surge*, PROC. NAT’L. ACAD. SCI. 121(40): 1–83, 1 (“We find from inverse analysis of GOSAT satellite observations that emissions from the wet tropics drove the 2010–2019 increase and the subsequent 2020–2022 surge, while emissions from northern mid-latitudes decreased. The 2020–2022 surge is principally contributed by emissions in Equatorial Asia (43%) and Africa (30%). Wetlands are the major drivers of the 2020–2022 emission increases in Africa and Equatorial Asia because of tropical inundation associated with La Niña conditions, consistent with trends in the GRACE terrestrial water storage data.”); Lin X., *et al.* (2024) *Recent methane surges reveal heightened emissions from tropical inundated areas*, NAT. COMMUN. 15(1): 1–11, 5 (“In summary, the record high CH_4 growth rates in 2020 and 2021 revealed heightened emissions from inundated areas in the tropical and boreal regions. Strong and persistent emission surges were found simultaneously over the Niger River basin, the Congo basin, the Sudd swamp, the Ganges floodplains, the Southeast Asian deltas, and Hudson Bay lowlands, coincident with elevated groundwater and warming in the north, and potentially linked to La Niña conditions prevailing since 2020. Our main findings on heightened emissions from both tropical and boreal wetlands, along with evidence from other bottomup or top-down studies[10,39,53–56], suggest recent intensification of wetland methane emissions and probable strong positive wetland climate feedback[57].”); *and* Michel S. E., Lan X., Miller J., Tans P., Clark J. R., Schaefer H., Sperlich P., Brailsford G., Morimoto S., Moossen H., & Li J. (2024) *Rapid shift in methane carbon isotopes suggests microbial emissions drove record high atmospheric methane growth in 2020–2022*, PROC. NAT’L. ACAD. SCI. 121(44): 1–3, 1 (“In this work, we use measurements of the ^{13}C:^{12}C ratio of CH4 (expressed as $\delta^{13}C$-CH_4) from NOAA’s Global Greenhouse Gas Reference Network and a box model to investigate potential drivers for the rapid CH_4 growth. These measurements show that the record-high CH_4 growth in 2020–2022 was accompanied by a sharp decline in $\delta^{13}C$-CH_4, indicating that the increase in CH_4 abundance was mainly driven by increased emissions from microbial sources such as wetlands, waste, and agriculture.”).

[116] Kleinen T., Gromov S., Steil B., & Brovkin V. (2021) *Atmospheric methane underestimated in future climate projections*, ENVIRON. RES. LETT. 16(9): 1–14, 4–5 (“In the case of the low radiative forcing scenarios SSP1–1.9 and SSP1–2.6, the concentration maximum occurs at the end of the historical period and does not differ significantly between our experiments and the published scenarios. The concentration decline after that maximum, however, occurs much more slowly in our experiments, leading to higher atmospheric methane concentrations than in the published scenarios. For the moderate to high warming scenarios SSP2–4.5, SSP3–7.0 and SSP5–8.5, however, the evolution of atmospheric methane is much more dramatic. Here, maximum atmospheric concentrations become substantially higher than in the published scenarios and stay at a very high level until the end of the experiments in 3000 CE. For SSP2–4.5, the maximum in CH_4 is 50% higher than published previously, for SSP3–7.0 it is 131% higher and for SSP5–8.5 it is 130% higher.”). *See also* Rehder Z., Kleinen T., Kutzbach L., Stepanenko V., Langer M., & Brovkin V. (2023) *Simulated methane emissions from Arctic ponds are highly sensitive to warming*, BIOGEOSCI. 20(14): 2837–2855, 2838 (“Most Arctic ponds emit predominantly contemporary, recently fixed, carbon (Negandhi et al., 2013; Bouchard et al., 2015; Dean et al., 2020). However, newly-formed ice-wedge ponds might emit older carbon than the average Arctic pond. When the permafrost adjacent to the thawing ice wedge degrades, old carbon can leech from the thawed sediments into the pond fueling methanogenesis (Langer et al., 2015; Preskienis et al., 2021) and exerting a positive climatic feedback. Furthermore, the composition of the ponds’ methanogenic communities might change in response to the warming Arctic.”); 2849 (“While ponds are not hotspots of methane emissions in our study area under the current climate, our model simulations indicate that they will become stronger methane sources under further warming. We project an increase of pond methane emissions of 1.33 g CH_4 m^{-2} $year^{-1}$ °C^{-1} .”).

[117] Peng S., Lin X., Thompson R. L., Xi Y., Liu G., Hauglustaine D., Lan X., Poulter B., Ramonet M., Saunois M., Yin Y., Zhang Z., Zheng B., & Ciais P. (2022) *Wetland emission and atmospheric sink changes explain methane growth in 2020*, NATURE 612(7940): 477–482, 481 ("In summary, our results show that an increase in wetland emissions, owing to warmer and wetter conditions over wetlands, along with decreased OH, contributed to the soaring methane concentration in 2020. The large positive MGR anomaly in 2020, partly due to wetland and other natural emissions, reminds us that the sensitivity of these emissions to interannual variation in climate has had a key role in the renewed growth of methane in the atmosphere since 2006. The wetland methane–climate feedback is poorly understood, and this study shows a high interannual sensitivity that should provide a benchmark for future coupled CH_4 emissions–climate models. We also show that the decrease in atmospheric CH_4 sinks, which resulted from a reduction of tropospheric OH owing to less NO_x emissions during the lockdowns, contributed 53 ± 10% of the MGR anomaly in 2020 relative to 2019. Therefore, the unprecedentedly high methane growth rate in 2020 was a compound event with both a reduction in the atmospheric CH_4 sink and an increase in Northern Hemisphere natural sources. With emission recovery to pre-pandemic levels in 2021, there could be less reduction in OH. The persistent high MGR anomaly in 2021 hints at mechanisms that differ from those responsible for 2020, and thus awaits an explanation."). *See also* Qu Z., Jacob D. J., Zhang Y., Shen L., Varon D. J., Lu X., Scarpelli T., Bloom A., Worden J., & Parker R. J. (2022) *Attribution of the 2020 surge in atmospheric methane by inverse analysis of GOSAT observations*, ENVIRON. RES. LETT. 17(9): 1–8, 6 ("The inversion shows an increase in the methane growth rate from 28 Tg a^{-1} in 2019 to 59 Tg a^{-1} in 2020, consistent with observations. This implies a forcing on the methane budget away from a steady state by 36 Tg a^{-1} from 2019 to 2020, 86% (82 ± 18% in the nine-member inversion ensemble) of which is from the increase in emissions between the two years and the rest is from the decrease in tropospheric OH. Changes in methane mass offset the forcing by 5 Tg a^{-1} . The global mean OH concentration decreases by 1.2% (1.6 ± 1.5%) from 2019 to 2020, which could be due to reduced NO_x emissions from COVID-19 decreases in economic activity but accounts for only a small fraction of the methane surge. We find that half of the increase in methane emissions from 2019 to 2020 is due to Africa. High precipitation and flooding in East Africa leading to increased wetland methane emissions could explain the increase. We also find a large relative increase in Canadian emissions, also apparently driven by wetlands..").

[118] Shindell D., Sadavarte P., Aben I., Bredariol T. de O., Dreyfus G., Höglund-Isaksson L., Poulter B., Saunois M., Schmidt G. A., Szopa S., Rentz K., Parsons L., Qu Z., Faluvegi G., & Maasakkers J. D. (2024) *The methane imperative*, FRONT. SCI. 2: 1–28, 3 ("The observed growth rates are roughly 1.5- to 2.5-fold higher than the multi-model mean baseline or bottom-up projections from 2020 to 2022 (Figure 2). The observed growth rates also exceed any individual model's baseline projections during that period. … That real-world methane growth rates exceed baseline projections therefore indicates that policies may have to be even stronger than those in existing analyses to reach the Paris Agreement's goals. Indeed, comparisons of observed atmospheric growth rates with those in 1.5°C-consistent scenarios (using the 2018 IPCC scenarios that did not include observations past 2017) show enormous differences (Figure 2), emphasizing how much stronger policies need to be to reach low-warming goals."); *discussed in* Zaelke D. (2 September 2024) *Mandatory mitigation to meet the methane imperative*, FRONTIERS POLICY LABS ("The *Frontiers in Science* lead article "The methane imperative", by Shindell et al. (5), provides definitive evidence demonstrating methane mitigation's planet-saving ability to reduce near-term warming. This starts with observational evidence showing that methane growth rates are reaching the greatest values ever recorded—far above levels consistent with the 1.5–2ºC temperature limits of the Paris Agreement—and the recognition that mandatory mitigation measures are therefore needed. The authors explain that failure to cut methane will eat up a sizable portion of the remaining carbon budget for 1.5ºC, which, on current course, will be exhausted by 2030. As the carbon budget shrinks, the need for strategies to reduce CO_2 and methane from the atmosphere grows.").

[119] United Nations Environment Programme & Climate & Clean Air Coalition (2022) GLOBAL METHANE ASSESSMENT: 2030 BASELINE REPORT, 6 ("One of the key conclusions of the GMA was that currently available technological measures and policies could reduce emissions from the three main anthropogenic methane emitting sectors by as much as 45 per cent of baseline emissions levels by 2030 (approximately 180 Mt per year in 2030). Baseline emissions scenarios assume implementation of existing policies and commitments but do not include additional mitigation action. Furthermore, such a reduction would be consistent with the range of methane mitigation called for in the Intergovernmental Panel on Climate Change's (IPCC) least cost-pathways that limit global warming

to 1.5°C in this century so long as it occurs alongside simultaneous reductions of other major climate forcers including carbon dioxide and short-lived climate pollutants. …The objectives of this Report include a more complete characterization of future baseline emissions, as well as easing comparison of GMA conclusions, which are communicated against approximate baseline emission levels in 2030, against the GMP target, which is set against 2020 emissions levels. This analysis also allows us to highlight the importance of early and targeted methane mitigation by assessing the climate benefits of the GMP target against expected increasing methane emissions under the baseline emissions scenarios, and compare them to the impact of addressing methane solely through a decarbonization strategy."); 18 ("We conclude that the most probable range of projected increases in annual emissions between 2020 and 2030 is ~20-50 Mt based on the combination of IAM and bottom-up estimates though a broader range of 5-75 Mt is plausible."); 23 ("As such, we calculated the mean across the models using equal weighting of the IAMs and bottom up models for agriculture and energy but the bottom up models only for waste. This yields a growth of 34 Mt per year (range 25-49) rather than the 31 Mt per year using equal weighting for all sectors, and we adopt this value and range as the 'best estimate' for this report.").

[120] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS, 8 ("Reducing human-caused methane emissions is one of the most cost-effective strategies to rapidly reduce the rate of warming and contribute significantly to global efforts to limit temperature rise to 1.5°C. Available targeted methane measures, together with additional measures that contribute to priority development goals, can simultaneously reduce human-caused methane emissions by as much as 45 per cent, or 180 million tonnes a year (Mt/yr) by 2030. This will avoid nearly 0.3°C of global warming by the 2040s and complement all long-term climate change mitigation efforts. It would also, each year, prevent 255 000 premature deaths, 775 000 asthma related hospital visits, 73 billion hours of lost labour from extreme heat, and 26 million tonnes of crop losses globally.").

[121] United Nations Environment Programme & Climate & Clean Air Coalition (2022) GLOBAL METHANE ASSESSMENT: 2030 BASELINE REPORT, 11 ("Using the results from the 2021 Global Methane Assessment, we calculate that Global Methane Pledge would provide additional benefits worldwide through 2050, beyond keeping the planet cool, including: - Prevention of roughly 200,000 premature deaths per year due to ozone exposure - Avoidance of ~580 million tonnes of yield losses to wheat, maize (corn), rice and soybeans per year - Avoidance of ~$500 billion (2018 US$) per year in losses per year due to non-mortality health impacts, forestry and agriculture - Avoidance of ~1,600 billion lost work hours per year due to heat exposure.").

[122] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS, 78 ("The total valuation per tonne of methane for all market and non-market impacts assessed here is roughly US$ 4 300 using a cross-nation income elasticity for WTP of 1.0 and US$ 7 900 using an elasticity of 0.4 (Figure 3.19) – values are ~US$ 150 per tonne larger for fossil-related emissions. This value is dominated by mortality effects, of which US$ 2 500 are due to ozone and ~US$ 700 are due to heat using the more conservative 500 deaths per million tonnes of methane of this analysis' two global-scale estimates and a WTP income elasticity of 1.0, followed by climate impacts.").

[123] International Energy Agency (2023) CREDIBLE PATHWAYS TO 1.5 °C - FOUR PILLARS FOR ACTION IN THE 2020S, 1–15, 11 ("In the NZE Scenario, methane emissions from the energy sector fall by around 75% between 2020 and 2030 and total methane emissions from human activity fall by around 45%. The IEA's latest update of its Global Methane Tracker found that methane emissions from oil and gas alone could be reduced by 75% with existing technologies. Around $100 billion in total investment is needed over the period to 2030 to achieve this reduction—equivalent to less than 3% of oil and gas net income in 2022. To address methane emissions from fossil energy production and consumption, countries covering over half of global gas imports and over one-third of global gas exports released a Joint Declaration from Energy Importers and Exporters on Reducing Greenhouse Gas Emissions from Fossil Fuels at COP27 calling for minimizing flaring, methane, and CO_2 emissions across the supply chain to the fullest extent practicable.").

[124] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS, 21 ("The short lifetime of methane, and

the quick response of methane abundance to reduced emissions described earlier, mean that any action taken to reduce emissions will have an immediate pay off for climate in addition to the current and near-future human health and agricultural production. Observations over the past few decades have shown that decreased emissions lead quickly to lower methane levels relative to those that could be expected in the absence of the decreases. That is, there are no mechanisms that offset the decreases even though there are significant natural sources. Simply put, natural emissions do not make up for the decrease in anthropogenic emission. Indeed, the expectation that a reduction in emissions will yield quick results, in the order of a decade, is confirmed and emphasizes the importance of methane.").

[125] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS, 21 ("This is because a realistically paced phase-out of fossil fuels, or even a rapid one under aggressive decarbonization, is likely to have minimal net impacts on near-term temperatures due to the removal of co-emitted aerosols (Shindell and Smith 2019). As methane is the most powerful driver of climate change among the short-lived substances (Myhre et al. 2013), mitigation of methane emissions is very likely to be the most powerful lever in reducing near-term warming. This is consistent with other assessments; for example, the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5) showed that methane controls implemented between 2010 and 2030 would lead to a larger reduction in 2040 warming than the difference between RCPs 2.6, 4.5 and 6.0 scenarios. (The noted IPCC AR5-era scenarios are called representative concentration pathways (RCPs, with the numerical value indicating the target radiative forcing in 2100 (Kirtman et al. 2013))."). *See also* Ocko I. B., Sun T., Shindell D., Oppenheimer M., Hristov A. N., Pacala S.W., Mauzerall D. L., Xu Y., & Hamburg S. P. (2021) *Acting rapidly to deploy readily available methane mitigation measures by sector can immediately slow global warming*, ENVIRON. RES. LETT. 16(5): 1–11, 1 ("Pursuing all mitigation measures now could slow the global-mean rate of near-term decadal warming by around 30%, avoid a quarter of a degree centigrade of additional global-mean warming by midcentury, and set ourselves on a path to avoid more than half a degree centigrade by end of century. On the other hand, slow implementation of these measures may result in an additional tenth of a degree of global-mean warming by midcentury and 5% faster warming rate (relative to fast action), and waiting to pursue these measures until midcentury may result in an additional two tenths of a degree centigrade by midcentury and 15% faster warming rate (relative to fast action).").

[126] United Nations Environment Programme & World Meteorological Organization (2011) INTEGRATED ASSESSMENT OF BLACK CARBON AND TROPOSPHERIC OZONE, 254, 262 ("Evaluating global mean temperature change, it was found that the targeted measures to reduce emissions of methane and BC could greatly reduce warming rates over the next few decades (Figure 6.1; Box 6.1). When all measures are fully implemented, warming during the 2030s relative to the present would be only half as much as in the reference scenario. In contrast, even a fairly aggressive strategy to reduce CO_2 emissions, as for the CO_2-measures scenario, does little to mitigate warming until after the next 20-30 years (Box 6.2)."); "Large impacts of the measures examined here were also seen for the Arctic despite the minimal amount of emissions currently taking place there. This occurs due to the high sensitivity of the Arctic both to pollutants that are transported there from remote sources and to radiative forcing that takes place in areas of the northern hemisphere outside the Arctic. The 16 measures examined here, including the measures on pellet stoves and coal briquettes, reduce warming in the Arctic by 0.7 ºC (range 0.2 to 1.3 ºC) at 2040. This is a large portion of the 1.1 ºC (range 0.7 to 1.7 ºC) warming projected under the reference scenario for the Arctic, and hence implementation of the measures would be virtually certain to substantially slow, but not halt, the pace of Arctic climate change.").

[127] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS, Figure 5.1.

[128] Sun T., Ocko I. B., & Hamburg S. P. (2022) *The value of early methane mitigation in preserving Arctic summer sea ice*, ENVIRON. RES. LETT. 17(4): 1–11, 1 ("While drastic cuts in carbon dioxide emissions will ultimately control the fate of Arctic summer sea ice, we show that simultaneous early deployment of feasible methane mitigation measures is essential to avoiding the loss of Arctic summer sea ice this century. In fact, the benefit of combined methane and carbon dioxide mitigation on reducing the likelihood of a seasonally ice-free Arctic can be greater than the simple sum of benefits from two independent greenhouse gas policies. The extent to which methane mitigation can help preserve Arctic summer sea ice depends on the implementation timeline. The benefit of methane mitigation is maximized when all technically feasible measures are implemented within this decade, and it decreases with each

decade of delay in implementation due to its influence on end-of-century temperature. A key insight is that methane mitigation substantially lowers the risk of losing Arctic summer sea ice across varying levels of concomitant carbon dioxide mitigation.").

[129] Nzotungicimpaye C. M., MacIsaac A. J., & Zickfeld K. (2023) *Delaying methane mitigation increases the risk of breaching the 2 °C warming limit*, COMMUN. EARTH. ENVIRON. 4(250): 1–8, 2–3 ("The timing of CH_4 mitigation affects peak levels of [CH_4], [CO_2], and surface air temperature (SAT) in the future. According to our model, every 10-year delay in CH_4 mitigation increases the [CH_4] peak by 150-180 ppb (Fig. 2b). As such, delaying CH_4 mitigation to the 2040-2050 decade will increase the [CH_4] peak by 450–540 ppb relative to CH_4 mitigation initiated at or around 2020. The [CH_4] increase has a direct effect on global mean surface air temperature (SAT). For every 10-year delay in CH_4 mitigation, our model simulates an additional peak warming of ~0.1 °C (Fig. 2d). Delaying CH_4 mitigation to or around mid-century will increase the peak warming by 0.2–0.3 °C relative to a CH_4 mitigation initiated at present-day. Through feedback mechanisms operating in the Earth system (discussed below), one indirect effect of delaying CH_4 mitigation manifests with atmospheric CO_2 concentration ([CO_2]). Our model suggests that every 10-year delay in CH_4 mitigation implies an increase in the [CO_2] peak by 2-3 ppm (Fig. 2c). Consequently, delaying CH_4 mitigation to the 2040-2050 decade will increase the [CO_2] peak by 6-9 ppm relative to CH_4 mitigation at present-day. Relative to the early mitigation scenario (SSP1-2.6), delaying CH_4 mitigation to the 2040-2050 decade implies more [CH_4] (~200 ppb) and warming (~0.2 °C) at the year 2100 (Fig. 2b, d and Supplementary Note 3).").

[130] Nzotungicimpaye C. M., MacIsaac A. J., & Zickfeld K. (2023) *Delaying methane mitigation increases the risk of breaching the 2 °C warming limit*, COMMUN. EARTH. ENVIRON. 4(250): 1–8, 2–3 ("For every 10-year delay in CH_4 mitigation, our model simulates an additional peak warming of ~0.1 °C (Fig. 2d). Delaying CH_4 mitigation to or around mid-century will increase the peak warming by 0.2–0.3 °C relative to a CH_4 mitigation initiated at present-day…. In our model simulations, SAT changes are influenced by biogeochemical feedbacks in addition to the timing of CH_4 mitigation. In particular, we find that the feedback of SAT changes on the atmospheric CO_2 concentration (referred to as the carbon-climate feedback) contributes to increasing peak SAT differences between early and delayed CH_4 mitigation. While we prescribe the same anthropogenic CO_2 emissions in all our model simulations (See Methods), atmospheric CO_2 levels are projected to be higher for delayed CH_4 mitigation scenarios than for early CH_4 mitigation scenarios (Fig. 2c). In comparison to early CH_4 mitigation, delayed CH_4 mitigation results in high [CH_4] levels that lead to high SAT levels. Enhanced global warming results in high [CO_2] levels, which in turn contribute to increase the SAT differences between early and delayed CH_4 mitigation scenarios. Such feedbacks between SAT and [CO_2] involve the response of natural CO_2 sinks to global warming and climate change. For instance, increased SAT enhances the release of CO_2 through soil respiration and weakens the uptake of atmospheric CO_2 by oceans through the solubility pump, resulting in enhanced [CO_2] and an amplification of global warming14. Overall, we deduce that the carbon-climate feedback amplifies the SAT response in late versus early CH_4 mitigation scenarios (Fig. 2d and Fig. 3). To quantify the contribution of the carbon-climate feedback to additional peak warming from delayed CH_4 mitigation, we performed additional model simulations with prescribed CO_2 concentration from the early mitigation scenario (i.e. Early CH_4 Mitig SSP1-2.6). These model simulations suppress the warming signal from delayed CH_4 mitigation that is due to the carbon-climate feedback, and their difference with our standard model simulations allows to quantify the magnitude of the feedback. According to our results, the contribution of the carbon-climate feedback to the peak warming increases for every 10-year delay in CH_4 mitigation (Fig. 3). The peak warming attributable to the feedback ranges from ~0.03 °C for CH_4 mitigation initiated in 2020 to ~0.06 °C for CH_4 mitigation initiated in 2050 (Fig. 3).").

[131] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS, 10 ("The levels of methane mitigation needed to keep warming to 1.5°C will not be achieved by broader decarbonization strategies alone. The structural changes that support a transformation to a zero-carbon society found in broader strategies will only achieve about 30 per cent of the methane reductions needed over the next 30 years. Focused strategies specifically targeting methane need to be implemented to achieve sufficient methane mitigation. At the same time, without relying on future massive-scale deployment of unproven carbon removal technologies, expansion of natural gas infrastructure and usage is incompatible with keeping warming to 1.5°C. (Sections 4.1, 4.2 and 4.3)").

[132] Intergovernmental Panel on Climate Change (2022) *Summary for Policymakers*, *in* CLIMATE CHANGE 2022: MITIGATION OF CLIMATE CHANGE, *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Shukla P. R., Skea J., Slade R., Al Khourdajie A., van Diemen R., McCollum D., Pathak M., Some S., Vyas P., Fradera R., Belkacemi M., Hasija A., Lisboa G., Luz S., & Malley J. (eds.), 23, 24 ("Deep GHG emissions reductions by 2030 and 2040, particularly reductions of methane emissions, lower peak warming, reduce the likelihood of overshooting warming limits and lead to less reliance on net negative CO_2 emissions that reverse warming in the latter half of the century. Reaching and sustaining global net zero GHG emissions results in a gradual decline in warming. (*high confidence*) (Table SPM.1)").

[133] Intergovernmental Panel on Climate Change (2022) *Summary for Policymakers*, *in* CLIMATE CHANGE 2022: MITIGATION OF CLIMATE CHANGE, *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Shukla P. R., Skea J., Slade R., Al Khourdajie A., van Diemen R., McCollum D., Pathak M., Some S., Vyas P., Fradera R., Belkacemi M., Hasija A., Lisboa G., Luz S., & Malley J. (eds.), 17 ("C.1.2 In modelled pathways that limit warming to 2°C (>67%) assuming immediate action, global net CO_2 emissions are reduced compared to modelled 2019 emissions by 27% [11–46%] in 2030 and by 52% [36-70%] in 2040; and global CH_4 emissions are reduced by 24% [9–53%] in 2030 and by 37% [20–60%] in 2040. In pathways that limit warming to 1.5°C (>50%) with no or limited overshoot global net CO_2 emissions are reduced compared to modelled 2019 emissions by 48% [36–69%] in 2030 and by 80% [61-109%] in 2040; and global CH_4 emissions are reduced by 34% [21–57%] in 2030 and 44% [31-63%] in 2040. There are similar reductions of non-CO_2 emissions by 2050 in both types of pathways: CH_4 is reduced by 45% [25–70%]; N_2O is reduced by 20% [-5 – 55%]; and F-Gases are reduced by 85% [20–90%]. [FOOTNOTE 44] Across most modelled pathways, this is the maximum technical potential for anthropogenic CH_4 reductions in the underlying models (*high confidence*). Further emissions reductions, as illustrated by the IMP-SP pathway, may be achieved through changes in activity levels and/or technological innovations beyond those represented in the majority of the pathways (*medium confidence*). Higher emissions reductions of CH_4 could further reduce peak warming. (*high confidence*) (Figure SPM.5)"). *See also* Intergovernmental Panel on Climate Change (2023) AR6 SYNTHESIS REPORT: CLIMATE CHANGE 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 57 ("All global modelled pathways that limit warming to 2°C (>67%) or lower by 2100 involve reductions in both net CO_2 emissions and non-CO_2 emissions (see Figure 3.6) (*high confidence*). For example, in pathways that limit warming to 1.5°C (>50%) with no or limited overshoot, global CH_4 (methane) emissions are reduced by 34% [21–57%] below 2019 levels by 2030 and by 44% [31–63%] in 2040 (*high confidence*). Global CH_4 emissions are reduced by 24% [9–53%] below 2019 levels by 2030 and by 37% [20–60%] in 2040 in modelled pathways that limit warming to 2°C with action starting in 2020 (>67%) (*high confidence*).").

[134] Reisinger A. (2024) *Why addressing methane emissions is a non-negotiable part of effective climate policy*, FRONT. SCI. 2: 1–5, 1 ("Deep reductions in future methane (CH4) emissions alongside carbon dioxide (CO2) are non-negotiable if we wish to limit global warming to well below 2°C, let alone 1.5°C, but action on CH_4 cannot substitute inaction on CO_2: reaching at least net zero CO_2 emissions globally remains a prerequisite for limiting warming at any level."); 4 ("The large gap between the potential and currently realized extent of CH_4 mitigation makes it clear that stronger and more consistent policies are needed to motivate and regulate companies to reduce CH_4 emissions. Strikingly, only about 13% of global CH_4 emissions are covered by targeted policies, and a significant share of those policies focus on monitoring rather than reduction and rely on information and voluntary action rather than mandatory pricing or regulation (9). By comparison, more than 53% of global total emissions are covered by climate laws (10).").

[135] Olczak M., Piebalgs A., & Balcombe P. (2023) *A global review of methane policies reveals that only 13% of emissions are covered with unclear effectiveness*, ONE EARTH 6(5): 519–535, 530 ("By exploring the state of the art of methane policies via a synthesis of their scope, stringency, and effectiveness, in this review, we uncover that, despite the growing scientific evidence, methane emission reduction remains underexplored, with only ~13% (min. 10%, max. 17%) of global methane emissions covered by direct methane mitigation policies. Methane policy development is recent (last one or two decades) and concentrated in three regions (North America, Europe, and parts of Asia-Pacific). Unlocking underexplored mitigation opportunities will require policymakers to target the blind spots: coverage of

policies (e.g., underregulated sources across the supply chain and facility/project lifetime) and their stringency (e.g., measurable reduction objectives, proper monitoring, and verification and enforcement).").

[136] Shindell D., Sadavarte P., Aben I., Bredariol T. de O., Dreyfus G., Höglund-Isaksson L., Poulter B., Saunois M., Schmidt G. A., Szopa S., Rentz K., Parsons L., Qu Z., Faluvegi G., & Maasakkers J. D. (2024) *The methane imperative*, FRONT. SCI. 2: 1–28, 10 ("In addition to the impacts on warming, a 20-year delay in methane reductions from 2020 to 2040 would also lead to 4.2 (1.3–6.8; 95% confidence) million additional premature deaths due to ozone exposure by 2050 that could have been avoided with rapid methane reductions based on our standard epidemiological estimates (Figure 6B). That value becomes ~8.8 (5.5–11.1) million additional deaths using alternative cardiovascular and additional child-mortality relationships (Analysis E). In addition to reducing early deaths, cutting methane emissions will reduce near-term warming impacts on labor, which grow nonlinearly with warming (100). We used our climate Analysis E as the basis to estimate corresponding labor effects of changing heat exposure (Analysis F). Assuming outdoor workers are in the shade, achieving 1.5°C-consistent methane abatement under SSP2 avoids roughly US$250 billion in worldwide potential heavy outdoor labor losses by 2050 (range US$190–US$390 over impact functions; values in 2017 US$ purchasing power parity). However, for outdoor workers in the sun, benefits would be roughly US$315 billion (range US$211–US$475). These values, for heavy outdoor labor only, are not comparable to impacts covering medium and light labor (for which the evidence base is weaker).").

[137] Jackson R. B., Saunois M., Martinez A., Canadell J. G., Yu X., Li M., Poulter B., Raymond P. A., Regnier P., Ciais P., Davis S. J., & Patra P. K. (2024) *Human activities now fuel two-thirds of global methane emissions*, ENVIRON. RES. LETT. 19(10): 1–11, 9 ("At least two-thirds of global methane emissions are now attributable to anthropogenic sources, an outcome that cannot continue if we are to maintain a habitable climate."). *See also* Saunois M., *et al.* (2024) *Global Methane Budget 2000–2020*, EARTH SYST. SCI. DATA DISCUSSIONS (*preprint*).

[138] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS, 25 ("Anthropogenic methane emissions come primarily from three sectors: fossil fuels, ~35 per cent; agriculture, ~40 per cent; and waste, ~20 per cent.").

[139] United Nations Environment Programme & Climate & Clean Air Coalition (2022) GLOBAL METHANE ASSESSMENT: 2030 BASELINE REPORT, 6 ("One of the key conclusions of the GMA was that currently available technological measures and policies could reduce emissions from the three main anthropogenic methane emitting sectors by as much as 45 per cent of baseline emissions levels by 2030 (approximately 180 Mt per year in 2030). Baseline emissions scenarios assume implementation of existing policies and commitments but do not include additional mitigation action. Furthermore, such a reduction would be consistent with the range of methane mitigation called for in the Intergovernmental Panel on Climate Change's (IPCC) least cost-pathways that limit global warming to 1.5°C in this century so long as it occurs alongside simultaneous reductions of other major climate forcers including carbon dioxide and short-lived climate pollutants. …The objectives of this Report include a more complete characterization of future baseline emissions, as well as easing comparison of GMA conclusions, which are communicated against approximate baseline emission levels in 2030, against the GMP target, which is set against 2020 emissions levels. This analysis also allows us to highlight the importance of early and targeted methane mitigation by assessing the climate benefits of the GMP target against expected increasing methane emissions under the baseline emissions scenarios, and compare them to the impact of addressing methane solely through a decarbonization strategy."); 18 ("We conclude that the most probable range of projected increases in annual emissions between 2020 and 2030 is ~20-50 Mt based on the combination of IAM and bottom-up estimates though a broader range of 5-75 Mt is plausible."); 23 ("As such, we calculated the mean across the models using equal weighting of the IAMs and bottom up models for agriculture and energy but the bottom up models only for waste. This yields a growth of 34 Mt per year (range 25-49) rather than the 31 Mt per year using equal weighting for all sectors, and we adopt this value and range as the 'best estimate' for this report."). *See also* United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS.

[140] Jackson R. B., *et al.* (2020) *Increasing anthropogenic methane emissions arise equally from agricultural and fossil fuel sources*, ENVIRON. RES. LETT. 15(7): 1–7, 6 ("Increased emissions from both the agriculture and waste sector and

the fossil fuel sector are likely the dominant cause of this global increase (figures 1 and 4), highlighting the need for stronger mitigation in both areas. Our analysis also highlights emission increases in agriculture, waste, and fossil fuel sectors from southern and southeastern Asia, including China, as well as increases in the fossil fuel sector in the United States (figure 4). In contrast, Europe is the only continent in which methane emissions appear to be decreasing. While changes in the sink of methane from atmospheric or soil uptake remains possible (Turner *et al* 2019), atmospheric chemistry and land-surface models suggest the timescales for sink responses are too slow to explain most of the increased methane in the atmosphere in recent years. Climate policies overall, where present for methane mitigation, have yet to alter substantially the global emissions trajectory to date.").

[141] Clean Air Task Force, *Oil and Gas Mitigation Program* (*last visited* 13 June 2023) ("Fortunately, most leaks are straightforward to repair (and fixing leaks is paid for by the value of the gas that is saved by repairing them). Further, finding leaks has become efficient with modern technology. The standard approach today is to use special cameras that can detect infrared light (think of night-vision goggles) which are tuned to make methane, which is invisible to our eyes, visible. They allow inspectors to directly image leaking gas in real time, with the ability to inspect entire components (not just connections and other areas most likely to leak) and pinpoint the precise source, making repair more straightforward. And, technology promises to make this process even more efficient (and cheaper) over the coming years. These technologies can be utilized to reduce harmful leak emissions, by using regular inspections as the lynchpin of rigorous "leak detection and repair" (LDAR) programs. These programs require operators to regularly survey all of their facilities for leaks and improper emissions, and repair all the leaks they identify in a reasonable time. For example, California requires operators to survey all sites four times a year. Colorado has a different approach, requiring operators of the largest sites to survey them monthly, but requiring less frequent inspections for site with smaller potential emissions.").

[142] Clean Air Task Force, *Oil and Gas Mitigation Program* (*last visited* 13 June 2023) (listing pneumatic equipment venting, compressor seal venting, tank venting, well completion venting, oil well venting and flaring, and dehydrator venting as sources of the "biggest mitigation opportunities.").

[143] Clean Air Task Force, *Oil and Gas Mitigation Program* (*last visited* 13 June 2023) ("Venting is even more harmful than flaring, since methane warms the climate so powerfully, and VOC and toxic pollutants are released unabated. Venting of this gas should be prohibited in all cases as an absolutely unnecessary source of harmful air pollution. There are numerous lowcost (and usually profitable) ways to utilize natural gas from oil wells. Flaring should be a last resort: only in the most extreme cases should oil producers be allowed to flare gas, and it should be strictly a temporary measure. Rules prohibiting venting of natural gas can easily reduce emissions by 95%.").

[144] Clean Air Task Force, *Oil and Gas Mitigation Program* (*last visited* 13 June 2023) ("Operators often vent and flare natural gas at oil wells. This waste occurs when oil producers, driven by the rush to Operators often vent and flare natural gas at oil wells. This waste occurs when oil producers, driven by the rush to sell oil, simply dispose of the gas from producing oil wells instead of building infrastructure (such as pipelines) to capture gas as soon as production begins. (In some cases, pipelines are never built and all of the gas the well produces over its lifetime is wasted in this way, as can be seen in sales records for individual wells available from state regulators.) While a substantial portion of this gas is flared off — wasting energy and producing large amounts of carbon dioxide and other pollutants — some is just dumped into the air, or vented. Even in cases where a gas pipeline is not connected, there are a variety of other technologies that operators can use to reduce associated gas flaring at oil wells. Venting is even more harmful than flaring, since methane warms the climate so powerfully, and VOC and toxic pollutants are released unabated. Venting of this gas should be prohibited in all cases as an absolutely unnecessary source of harmful air pollution. There are numerous lowcost (and usually profitable) ways to utilize natural gas from oil wells. Flaring should be a last resort: only in the most extreme cases should oil producers be allowed to flare gas, and it should be strictly a temporary measure. Rules prohibiting venting of natural gas can easily reduce emissions by 95%."). *See also* World Bank, *Zero Routine Flaring by 2030 Initiative Text* (*last visited* 13 June 2023) ("This "**Zero Routine Flaring by 2030" initiative** (the Initiative), introduced by the World Bank, brings together governments, oil companies, and development institutions who recognize the flaring situation described above is unsustainable from a resource management and environmental perspective, and who agree to cooperate to eliminate routine flaring no later than 2030.").

[145] United States Climate Alliance (2018) FROM SLCP CHALLENGE TO ACTION: A ROADMAP FOR REDUCING SHORT-LIVED CLIMATE POLLUTANTS TO MEET THE GOALS OF THE PARIS AGREEMENT, 13 ("Actions to improve manure management and to reduce methane from enteric fermentation have the potential to significantly reduce agricultural methane emissions across U.S. Climate Alliance states. Improving manure storage and handling, composting manure, utilizing pasture-based systems, or installing anaerobic digesters significantly reduces methane from manure management on dairy, swine, and other livestock operations. These practices may reduce methane from manure management by as much as 70 percent in U.S. Climate Alliance states (Appendix A) and can help improve soil quality and fertility, reduce water use and increase water quality, reduce odors, and decrease the need for synthetic fertilizers and associated greenhouse gas emissions. Promising technologies are also emerging that may cut methane emissions from enteric fermentation by 30 percent or more (Appendix A). Developing strategies that work for farmers and surrounding communities can significantly reduce methane emissions, increase and diversify farm revenues, and support water quality and other environmental benefits."). *See also* Höglund-Isaksson L., Gómez-Sanabria A., Klimont Z., Rafaj P., & Schöpp W. (2020) *Technical potentials and costs for reducing global anthropogenic methane emissions in the 2050 timeframe—results from the GAINS model*, ENVIRON. RES. COMM. 2(2): 1–21, 13–14 ("The technical abatement potential for agricultural sources is assessed at 21 percent below baseline emissions in year 2050. This includes relatively limited abatement potentials for livestock of 12 percent due to applicability limitations (see section S3.4. in the SI for details). Large farms with more than 100 LSU contribute about a third of global CH_4 emissions from livestock and for this group we find it technically feasible to reduce emissions by just over 30 percent below baseline emissions in year 2050 (see figures S6–2 in the SI). The available options include reduction of enteric fermentation emissions through animal feed changes (Gerberetal 2013, Hristov et al 2013) combined with implementation of breeding schemes that simultaneously target genetic traits for improved productivity and enhanced animal health/longevity and fertility. Increased productivity reduces system emissions by enabling the production of the same amount of milk using fewer animals. The dual objective in breeding schemes is important as a one-eyed focus on increased productivity leads to deteriorating animal health and fertility and a risk that system emissions increase due to a need to keep a larger fraction of unproductive replacement animals in the stock (Lovett et al 2006, Berglund 2008, Bell et al 2011). The enteric fermentation options are considered economically feasible for commercial/industrial farms with more than 100 LSU but not for smaller- and medium- sized farms. Breeding schemes are assumed to deliver impacts on emissions only after 20 years and feed changes are assumed applicable only while animals are housed indoor. Emissions from manure management can be reduced through treatment of manure in anaerobic digesters (ADs) with biogas recovery. To be efficient from both an economic and environmental point of view, a certain scale is needed to accommodate both the fixed investment of the AD plant and the time farmers spend carefully attending to and maintaining the process (for details see section 3.3.1.3 in Höglund-Isaksson et al 2018)."); *and* Borgonovo F., *et al*. (2019) *Improving the sustainability of dairy slurry with a commercial additive treatment*, SUSTAINABILITY 11(18): 1–14, 8 ("N_2O, CO_2, and CH_4 emissions, from the treated slurry, were respectively 100%, 22.9% and 21.5% lower than the control at T4 when the emission peaks were recorded.").

[146] In the U.S. alone, natural gas stoves emit 28.1 Gg of methane a year, among other climate pollutants that are hazardous to the environment and human health: *see* Lebel E. D., Finnegan C. J., Ouyang Z., & Jackson R. B. (2022) *Methane and NO_x Emissions from Natural Gas Stoves, Cooktops, and Ovens in Residential Homes*, ENVIRON. SCI. TECHNOL. 56(4): 2529–2539, 2529 ("Natural gas stoves in >40 million U.S. residences release methane (CH_4)─a potent greenhouse gas─through post-meter leaks and incomplete combustion. We quantified methane released in 53 homes during all phases of stove use: steady-state-off (appliance not in use), steady-state-on (during combustion), and transitory periods of ignition and extinguishment. We estimated that natural gas stoves emit 0.8–1.3% of the gas they use as unburned methane and that total U.S. stove emissions are 28.1 [95% confidence interval: 18.5, 41.2] Gg CH_4 year^{-1}. More than three-quarters of methane emissions we measured originated during steady-state-off. Using a 20-year timeframe for methane, annual methane emissions from all gas stoves in U.S. homes have a climate impact comparable to the annual carbon dioxide emissions of 500 000 cars. In addition to methane emissions, co-emitted health-damaging air pollutants such as nitrogen oxides (NO_x) are released into home air and can trigger respiratory diseases. In 32 homes, we measured NO_x (NO and NO_2) emissions and found them to be linearly related to the amount of natural gas burned ($r^2 = 0.76$; $p \ll 0.01$). Emissions averaged 21.7 [20.5, 22.9] ng NO_x J^{-1}, comprised of 7.8 [7.1, 8.4] ng NO_2 J^{-1} and 14.0 [12.8, 15.1] ng NO J^{-1}. Our data suggest that families who don't use their range hoods or

who have poor ventilation can surpass the 1-h national standard of NO_2 (100 ppb) within a few minutes of stove usage, particularly in smaller kitchens.").

[147] Höglund-Isaksson L., Gómez-Sanabria A., Zbigniew K., Rafaj P., & Schöpp W. (2020) *Technical potentials and costs for reducing global anthropogenic methane emissions in the 2050 timeframe—results from the GAINS model*, ENVIRON. RES. COMM. 2(2): 1–21, 16–17 ("An additional almost 10 percent of baseline emissions in 2050 could be removed at a marginal cost below 20 €/t CO_2eq by implementing proper waste and wastewater handling in China, India and the rest of South-East Asia. This would likely come with considerable co-benefits in the form of reduced air and water pollution.").

[148] United States Climate Alliance (2018) FROM SLCP CHALLENGE TO ACTION: A ROADMAP FOR REDUCING SHORT-LIVED CLIMATE POLLUTANTS TO MEET THE GOALS OF THE PARIS AGREEMENT, 15 ("Significant opportunities for reducing methane emissions from landfills and capturing value can be seized by reducing food loss and waste, diverting organic waste to beneficial uses, and improving landfill management. These and other actions collectively could reduce methane emissions from waste by an estimated 40-50 percent by 2030 (Appendix A). Such efforts could add value in our states by reducing emissions of volatile organic compounds and toxic air contaminants from landfills, recovering healthy food for human consumption in food insecure communities, supporting healthy soils and agriculture, generating clean energy and displacing fossil fuel consumption, and providing economic opportunities across these diverse sectors. Many of these benefits will accrue in low-income and disadvantaged communities."). *See also* Geyik Ö., Hadjikakou M., & Bryan B. A. (2022) *Climate-friendly and nutrition-sensitive interventions can close the global dietary nutrient gap while reducing GHG emissions*, NAT. FOOD. 4: 61–73, 61 ("Here, we estimate the non-CO_2 greenhouse gas emissions resulting from closing the world's dietary nutrient gap—that between country-level nutrient supply and population requirements—for energy, protein, iron, zinc, vitamin A, vitamin B12 and folate under five climate-friendly intervention scenarios in 2030. We show that improving crop and livestock productivity and halving food loss and waste can close the nutrient gap with up to 42% lower emissions (3.03 Gt CO_2eq yr^{-1}) compared with business-as-usual supply patterns with a persistent nutrient gap (5.48 Gt CO_2eq yr^{-1}).").

[149] Jackson R. B., *et al.* (2021) *Atmospheric methane removal: a research agenda*, PHILOS. TRANS. R. SOC. A 379(2210): 1–17, 3–4 ("Atmospheric methane removal may be needed to offset continued methane release and limit the global warming contribution of this potent greenhouse gas. Eliminating most anthropogenic methane emissions is unlikely this century, and sudden methane release from the Arctic or elsewhere cannot be excluded, so technologies for negative emissions of methane may be needed. Carbon dioxide removal (CDR) has a well-established research agenda, technological foundation and comparative modelling framework [23–28]. No such framework exists for methane removal. We outline considerations for such an agenda here. We start by presenting the technological Mt CH_4 yr^{-1} considerations for methane removal: energy requirements (§2a), specific proposed technologies (§2b), and air processing and scaling requirements (§2c). We then outline the climate and air quality impacts and feedbacks of methane removal (§3a) and argue for the creation of a Methane Removal Model Intercomparison Project (§3b), a multi-model framework that would better quantify the expected impacts of methane removal. In §4, we discuss some broader implications of methane removal."). *See also* Abernethy S., O'Connor F. M., Jones C. D., & Jackson R. B. (2021) *Methane removal and the proportional reductions in surface temperature and ozone*, PHILOS. TRANS. R. SOC. A 379(2210): 1–13, 6 ("Due to the temporal nature of effective cumulative removal, comparisons between methane and carbon dioxide depend on the timescale of interest. The equivalent of MCR for carbon dioxide, the TCRE, is 0.00048 ± 0.0001°C per Pg CO_2 [38], two orders of magnitude smaller than our MCR estimate of 0.21 ± 0.04°C per effective Pg CH_4 removed (figure 2). Accounting for the time delay for carbon dioxide removal due to the lagged response of the deep ocean, the TCRE for CO_2 removal may be even lower [39]. If 1 year of anthropogenic emissions was removed (0.36 Pg CH_4 [3] and 41.4 Pg CO_2 [40]), the transient temperature impact would be almost four times larger for methane than for CO_2 (0.075°C compared to 0.02°C). Using this example, however, maintaining a steady-state response of 0.36 Pg CH_4 effectively removed would require the ongoing removal of roughly 0.03Pg CH_4 yr^{-1}, since a removal rate of E/τ is required to maintain an effective cumulative removal of E.").

[150] Saunois M., *et al*. (2020) *The Global Methane Budget* 2000-2017, EARTH SYST. SCI. DATA 12(3): 1561–1623, 1561 ("For the 2008–2017 decade, global methane emissions are estimated by atmospheric inversions (a top-down approach) to be 576 Tg CH_4 yr^{-1} (range 550–594, corresponding to the minimum and maximum estimates of the model

ensemble). Of this total, 359 Tg CH_4 yr^{-1} or ~ 60 % is attributed to anthropogenic sources, that is emissions caused by direct human activity (i.e. anthropogenic emissions; range 336–376 Tg CH_4 yr^{-1} or 50 %–65 %).").

[151] Secretariat of the United Nations Framework Convention on Climate Change, *External Press Release, World Leaders Kick Start Accelerated Climate Action at COP26* (2 November 2021) ("This historic commitment, led by the US and EU alongside the UK COP26 presidency, equates to up to 40% of global methane emissions and 60% of global GDP. Today is also the first time a COP in recent history has hosted a major event on methane, with 103 countries, including 15 major emitters including Brazil, Nigeria and Canada, signing up to the Global Methane Pledge.").

[152] Global Methane Pledge (13 November 2024) *Factsheet: 2024 Global Methane Pledge Ministerial*, Press Release ("Spurred by the over $1 billion in grant funding announced at the 2023 UN Climate Change Conference (COP 28), international financial institutions have expanded methane-related project finance in the last year. This includes over 2 billion Euros ($2.1 billion) from the European Investment Bank, over 350 million Euros ($385 million) in loans and grants from the European Bank for Reconstruction and Development, and billions from the World Bank. The African Development Bank also recently launched a new $10 million program focused on gender-transformative methane reduction.").

[153] Global Methane Pledge, *Fast action on methane to keep a 1.5 ºC future within reach* (*last visited* 19 February 2025) ("The Global Methane Pledge (GMP) was launched at COP26 by the European Union and the United States who have been joined by many countries. In January 2025, GMP counted 159 participants. Since its launch, the GMP has generated unprecedented momentum for methane mitigation, with major work underway in six action areas including: the Energy Pathway, the Waste Pathway, the Food and Agriculture Pathway, Methane Plans and Policies, Data for Methane Action, and Finance for Methane Abatement. Such work is being supported by a broad range of leading international actors such as the Global Methane Initiative (GMI), the Global Methane Hub (GMH), the International Energy Agency (IEA), the United Nations Economic Commission for Europe (UNECE), and the World Bank.").

[154] Global Methane Hub (16 November 2024) *Global Methane Hub Announces $10 Million Data to Action Funding at COP29 Alongside Satellite Data Reveals* ("Since its inception in 2021, GMH has regranted $203 million to more than 132 organizations, impacting over 150 countries that account for over 80% of global methane emissions.").

[155] For a list of Global Methane Pledge participants, *see* https://www.globalmethanepledge.org/#pledges.

[156] United States Department of State (2 November 2021) *United States, European Union, and Partners Formally Launch Global Methane Pledge to Keep 1.5°C Within Reach*, Press Release ("Today, the United States, the European Union, and partners formally launched the Global Methane Pledge, an initiative to reduce global methane emissions to keep the goal of limiting warming to 1.5 degrees Celsius within reach. A total of over 100 countries representing 70% of the global economy and nearly half of anthropogenic methane emissions have now signed onto the pledge.").

[157] Global Methane Pledge, *About the Global Methane Pledge* (*last visited* 5 February 2024) ("With 155 country participants, representing a little over 50% of global anthropogenic methane emissions, we are well on our way to achieving the Pledge goal.").

[158] United States Department of State (11 October 2021) *Joint U.S.-EU Statement on the Global Methane Pledge* ("Countries joining the Global Methane Pledge commit to a collective goal of reducing global methane emissions by at least 30 percent from 2020 levels by 2030 and moving towards using highest tier IPCC good practice inventory methodologies to quantify methane emissions, with a particular focus on high emission sources. Successful implementation of the Pledge would reduce warming by at least 0.2 degrees Celsius by 2050.").

[159] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS, 9 ("Currently available measures could reduce emissions from these major sectors by approximately 180 Mt/yr, or as much as 45 per cent, by 2030. This is a cost-effective step required to achieve the United Nations Framework Convention on Climate Change (UNFCCC) 1.5° C target. According to scenarios analysed by the Intergovernmental Panel on Climate Change (IPCC), global

methane emissions must be reduced by between 40–45 per cent by 2030 to achieve least cost-pathways that limit global warming to 1.5° C this century, alongside substantial simultaneous reductions of all climate forcers including carbon dioxide and short-lived climate pollutants. (Section 4.1).”).

[160] United Nations Environment Programme & Climate & Clean Air Coalition (2022) GLOBAL METHANE ASSESSMENT: 2030 BASELINE REPORT, 32 (“Taking the 2020 emissions as 380 Mt, we can evaluate the climate impact of the methane reductions envisaged under the Global Methane Pledge. The GMP calls for a minimum reduction of 30per cent in comparison to 2020 emissions which translates to a decrease from 380 Mt to 270 Mt. In comparison with 2020 emissions, this lower level is a decrease of 113 Mt. In comparison with the projected value in 2030 based on the mean increase of 34 Mt from 2020 to 2030, however, this lower level represents a decrease of 150 Mt and a decrease of 36per cent compared to projected 2030 emissions levels. As noted, this 36 per cent reduction relative to the 2030 baseline is within the rage of 1.5°C scenarios, which call for 30-60 per cent reductions from 2030 levels assess in the GMA, but is smaller than the mean 45 per cent reduction across the large set of 1.5°C scenarios.”).

[161] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS, 8 (“Available targeted methane measures, together with additional measures that contribute to priority development goals, can simultaneously reduce human-caused methane emissions by as much as 45 per cent, or 180 million tonnes a year (Mt/yr) by 2030. This will avoid nearly 0.3°C of global warming by the 2040s and complement all long-term climate change mitigation efforts.”).

[162] United Nations Environment Programme & Climate & Clean Air Coalition (2022) GLOBAL METHANE ASSESSMENT: 2030 BASELINE REPORT, 11 (“Using the results from the 2021 Global Methane Assessment, we calculate that Global Methane Pledge would provide additional benefits worldwide through 2050, beyond keeping the planet cool, including: - Prevention of roughly 200,000 premature deaths per year due to ozone exposure - Avoidance of ~580 million tonnes of yield losses to wheat, maize (corn), rice and soybeans per year - Avoidance of ~$500 billion (2018 US$) per year in losses per year due to non-mortality health impacts, forestry and agriculture - Avoidance of ~1,600 billion lost work hours per year due to heat exposure.”).

[163] United Nations Environment Programme & Climate & Clean Air Coalition (2022) GLOBAL METHANE ASSESSMENT: 2030 BASELINE REPORT, 11 (“The global monetized benefits for all market and non-market impacts are approximately US$ 4 300 per tonne of methane reduced[1]. When accounting for these benefits nearly 85 per cent of the targeted measures have benefits that outweigh the net costs. The benefits of the annually avoided premature deaths.”).

[164] Karryos (2024) *The Global Methane Pledge, Three Years On: Partial Progress Report*, 2 (“[W]e measured annual methane emissions from 13 large fossil-fuel basins spread across nine major producing countries, including six GMP signatories. The countries were selected according to two main criteria: the size of their production and the availability of high-integrity, reliable data. They include large producers from a wide range of geographies, including North America (the US), the MENA region (Iran, Iraq, Kuwait and Algeria), Central Asia (Turkmenistan and Uzbekistan), Sub-Saharan Africa (South Africa) and Australia. The results overall are sobering. Aggregate methane emissions from the sample are continuing to increase, not decrease. This is cause for concern: the longer we take to reduce emissions, the steeper the abatement curve will have to be to achieve 2030 targets.”); 4 (“Overall, emissions from the sample of basins and countries under study increased by 7% in 2023 versus levels observed in the 2020 reference year, a headline figure that admittedly conceals distinct patterns across geographies.”).

[165] Karryos (2024) *The Global Methane Pledge, Three Years On: Partial Progress Report*, 8 (“The U.S. has been ramping up oil production at a fast pace in the three years since the onset of the Covid-19 pandemic, led by the Permian and other tight oil and gas basins (commonly referred to as shale oil and gas basins). Aggregate production of oil and gas from the three basins under review, measured in barrels of oil equivalent, surged by 21% in 2023 versus 2020, according to U.S. EIA estimates. This growth was likely the main factor behind the increase in associated methane emissions. On a brighter note, methane emissions from the three basins edged down in 2023 year-on-year, even as oil and gas production continued to increase. This resulted in a slight dip in the methane intensity of oil and gas

production, a dip that appears to have extended into the first half of 2024, leaving average methane intensity for the first six months slightly below 2020 levels.").

[166] Parties to the United Nations Framework Convention on Climate Change are required to report emissions on a gas-by-gas basis in units of mass. *See* United Nations Framework Convention on Climate Change, Dec. 18/CMA.1, FCCC/PA/CMA/2018/3/Add.2, at Annex ¶47 (2019) ("47. Each Party shall report estimates of emissions and removals for all categories, gases and carbon pools considered in the GHG inventory throughout the reported period on a gas-by-gas basis in units of mass at the most disaggregated level, in accordance with the IPCC guidelines referred to in paragraph 20 above, using the common reporting tables, including a descriptive summary and figures underlying emission trends, with emissions by sources listed separately from removals by sinks, except in cases where it may be technically impossible to separate information on emissions and removals in the LULUCF sector, and noting that a minimum level of aggregation is needed to protect confidential business and military information."). *See also* Allen M. R., *et al.* (2022) *Indicate separate contributions of long-lived and short-lived greenhouse gases in emission targets*, NPJ CLIM. ATMOS. SCI. 5(5): 1–4, 1 ("As researchers who have published over recent years on the issue of comparing the climate effects of different greenhouse gases, we would like to highlight a simple innovation that would enhance the transparency of stocktakes of progress towards achieving any multi-decade-timescale global temperature goal. In addition to specifying targets for total CO_2-equivalent emissions of all greenhouse gases, governments and corporations could also indicate the separate contribution to these totals from greenhouse gases with lifetimes around 100 years or longer, notably CO_2 and nitrous oxide, and the contribution from Short-Lived Climate Forcers (SLCFs), notably methane and some hydrofluorocarbons. This separate indication would support an objective assessment of the implications of aggregated emission targets for global temperature, in alignment with the UNFCCC Parties' Decision (4/CMA.1)1 to provide 'information necessary for clarity, transparency and understanding" in nationally determined contributions (NDCs) and long-term low-emission development strategies (LT-LEDSs).'").

[167] Abernethy S. & Jackson R. B. (2022) *Global temperature goals should determine the time horizons for greenhouse gas emission metrics*, ENVIRON. RES. LETT. 17(2): 1–10, 7 ("Although NDCs and long-term national pledges are currently insufficient to keep warming below 2 °C, let alone 1.5 °C [50–52], the time horizons used for emission metrics should nevertheless be consistent with that central goal of the Paris Agreement. We therefore support the use of the 20 year time horizon over the 100 year version, when binary choices between these two must be made, due to the better alignment of the former with the temperature goals of the Paris Agreement. The 50 year time horizon, not yet in widespread use but now included in IPCC AR6, is in fact the only time horizon that the IPCC presents that falls within the range of time horizons that align with the Paris Agreement temperature goals (24–58 years). However, to best align emission metrics with the Paris Agreement 1.5 ° C goal, we recommend the use of the 24 year time horizon, using 2045 as the end point time, with its associated $GWP_{1.5°C} = 75$ and $GTP_{1.5 °C} = 41$."), *discussed in* McKenna P. (9 February 2022) *To Counter Global Warming, Focus Far More on Methane, a New Study Recommends*, INSIDE CLIMATE NEWS ("The Environmental Protection Agency is drastically undervaluing the potency of methane as a greenhouse gas when the agency compares methane's climate impact to that of carbon dioxide, a new study concludes. The EPA's climate accounting for methane is "arbitrary and unjustified" and three times too low to meet the goals set in the Paris climate agreement, the research report, published Wednesday in the journal Environmental Research Letters, found."); *and* Rathi A. (15 February 2022) *The Case Against Methane Emissions Keeps Getting Stronger*, BLOOMBERG.

[168] Parties to the United Nations Framework Convention on Climate Change (UNFCCC) are required to report emissions on a gas-by-gas basis in units of mass. *See* United Nations Framework Convention on Climate Change, Dec. 18/CMA.1, FCCC/PA/CMA/2018/3/Add.2, at Annex ¶ 37 (2019) ("37. Each Party shall use the 100-year time-horizon global warming potential (GWP) values from the IPCC Fifth Assessment Report, or 100-year time-horizon GWP values from a subsequent IPCC assessment report as agreed upon by the CMA, to report aggregate emissions and removals of GHGs, expressed in CO_2 eq. Each Party may in addition also use other metrics (e.g., global temperature potential) to report supplemental information on aggregate emissions and removals of GHGs, expressed in CO_2 eq. In such cases, the Party shall provide in the national inventory document information on the values of the metrics used and the IPCC assessment report they were sourced from.").

[169] Cohen-Shields N., Sun T., Hamburg S. P., & Ocko I. B. (2023) *Distortion of sectoral roles in climate change threatens climate goals*, FRONT. CLIM. 5: 1–6, 4 ("Given how GWP100-based CO_2e calculations distort the roles of economic sectors in contributing to future warming, relying solely on GWP100 can lead to suboptimal policies and priorities by misleading climate actors from the top levels of government (e.g., U.S. NDC)[2] to grassroots organizations. This is because the importance of methane emissions in several sectors is systematically underestimated by GWP100.… there are examples of acknowledgment of the metric issue by stakeholders (such as work by the Irish Climate Change Advisory Council to establish multi-gas GHG budgets, as well as the State of New York publishing their emissions inventory using GWP20). Given that prioritizing sectoral mitigation efforts is often necessary under cost and political constraints, the current sectoral share distortion imposed by GWP100/CO_2e risks mis-prioritizing sectors for emissions reductions, undervaluing the benefits of methane-sector mitigation—especially in the near-term—and potentially overlooking important abatement measures. This can have implications for the temperature outcomes of climate policies. For example, if CO_2-dominated sectors are regularly prioritized for mitigation, the realized temperature benefits in the near-term will be lower than anticipated because the remaining warming impact from methane-dominated sectors will be underestimated. The bottom line is that GWP100 should never be singularly relied upon for emissions assessments.").

[170] Forster P., Storelvmo T., Armour K., Collins W., Dufresne J.-L., Frame D., Lunt D. J., Mauritsen T., Palmer M. D., Watanabe M., Wild M., & Zhang H. (2021) *Chapter 7: The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity Supplementary Material*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), Table 7.SM.7.

[171] Lynch J., Cain M., Pierrehumbert R., & Allen M. (2020) *Demonstrating GWP*: a means of reporting warming-equivalent emissions that captures the contrasting impacts of short- and long-lived climate pollutants*, ENVIRON. RES. LETT. 15(4): 044023, 1–13, 2 ("Following these behaviours, sustained emissions of an SLCP therefore result in a similar impact to a one-off release of a fixed amount of CO_2: both lead to a relatively stable long-term increase in radiative forcing. Thus an alternative means of equivalence can be derived, relating a change in the rate of emissions of SLCPs to a fixed quantity of CO_2…"). See also Mar K. A., Unger C., Walderdorff L. & Butler T. (2022) *Beyond* CO_2 *equivalence: The impacts of methane on climate, ecosystems, and health*, ENVIRON. SCI. POLICY 134: 127–136, 132 ("However, this practice of assigning "equivalence" belies the physical reality, namely that CH_4's impact on climate is distinct from CO_2's in several important ways, as described in Section 3. In effect, only the long-term climate impact of CH_4 (i.e., its radiative forcing over a 100-year time horizon) is robustly taken into account under the Kyoto Protocol and the Paris Agreement. Among other things, this means that CH_4's outsized contribution to near-term climate warming is overlooked…. The focus on CO_2 equivalence under the UNFCCC also leads to an information and transparency gap. The common practice of expressing mitigation targets in terms of aggregate CO_2e, without specifying which reductions come from which GHGs, compromises the ability of modelers to evaluate in detail how the climate will respond to pledged emission reductions; this is because the climate responds differently to the different climate forcers (Fig. 2).").

[172] Cain M., Lynch J., Allen M. R., Fuglestvedt J. S., Frame D. J., & Macey A. H. (2019) *Improved calculation of warming-equivalent emissions for short-lived climate pollutants*, NPJ CLIM. ATMOS. SCI. 2(29): 1–7, 4 ("We have used an empirical method to find a definition of GWP* that preserves the link between an emission and the warming it generates in the medium term up to 2100. The physical interpretation of equation 1 is that the flow term (with coefficient *r*) represents the fast climate response to a change in radiative forcing, generated by the atmospheric and ocean mixed-layer response.[30] The timescale of this response is about 4 years here.[31] The stock term (with coefficient *s*) represents the slower timescale climate response to a change in radiative forcing, due to the deep ocean response. This effect means that the climate responds slowly to past changes in radiative forcing, and is why the climate is currently far from equilibrium. We have approximated this response by treating a quarter of the climate response to a SLCP as "cumulative".").

[173] Rogelj J. & Schleussner C.-F. (2021) *Reply to Comment on `Unintentional unfairness when applying new greenhouse gas emissions metrics at country level'*, ENVIRON. RES. LETT. 16(6): 1–8, 2 ("These ethical issues arise from moving away from an emissions centered metric like GWP-100—where every unit of emissions of a certain

GHG is treated equally and independent of the emitter or timing of emissions—to metrics like GWP*—which focus on additional warming and where the treatment of a unit of emissions depends on the emitter and their emission history… Meanwhile, a group of the world's biggest diary producers seems happy to consider the grandfathering GWP* perspective and explicitly dismisses other fairness perspectives that would increase their companies' responsibility for reducing methane emissions (Cady 2020)."); *citing* Cady R. (2020) *A Literature Review of GWP*: A proposed method for estimating global warming potential (GWP*) of short-lived climate pollutants like methane*, GLOBAL DAIRY PLATFORM, *discussed in* Elgin B. (19 October 2021) *Beef Industry Tries to Erase Its Emissions With Fuzzy Methane Math*, BLOOMBERG GREEN.

[174] Global Methane Pledge (15 November 2024) *Open Letter to Global Methane Pledge Endorsers*.

[175] United States Department of State (17 June 2022) *U.S.-EU Joint Press Release on the Global Methane Pledge Energy Pathway*, Press Release ("Today, the United States, the European Union, and 11 countries launched the Global Methane Pledge Energy Pathway to catalyze methane emissions reductions in the oil and gas sector, advancing both climate progress and energy security…. **Countries and supporting organizations announced nearly $60 million in dedicated funding to support implementation of the Pathway.** Countries and supporting organizations have announced $59 million in dedicated funding and in-kind assistance in support of the GMP Energy Pathway that was announced at today's MEF, including: **$4 million** to support the **World Bank Global Gas Flaring Reduction Partnership (GGFR)**. The United States intends to support the transfer by the World Bank of at least $1.5 million in funding to the GGFR. **Germany** intends to provide $1.5 million, and **Norway** intends to provide approximately $1 million to GGFR. **$5.5 million** to support the **Global Methane Initiative (GMI)**. The **United States** will provide $3.5 million. Guided by the recommendations of the GMI, **Canada** will contribute $2 million over the next four years, as part of its global climate finance commitment, to support methane mitigation projects in developing countries including in the oil and gas sector. Up to **$9.5 million** from the UNEP **International Methane Emissions Observatory** to support scientific assessments of methane emissions and mitigation potential in the oil and gas sector that are aligned with the Global Methane Pledge Energy Pathway. Up to **$40 million** annually from the philanthropic **Global Methane Hub** to support methane mitigation in the fossil energy sector. These funds will be critical to improve methane measurements in the oil and gas sector, identify priority areas for methane mitigation, develop technical assessments for project development, strengthen regulator and operator capacity, support policy development and enforcement, and other essential activities to achieve reductions in methane emissions.").

[176] United States Department of State (17 November 2022) *Global Methane Pledge: From Moment to Momentum*, Press Release ("In the year since it launched at COP26, the Global Methane Pledge has generated unprecedented momentum for methane action. Country endorsements of the GMP have grown from just over 100 last year to 150, more than 50 countries have developed national methane action plans or are in the process of doing so, substantial new financial resources are being directed to methane action, and partners have launched "pathways" of policies and initiatives to drive methane reductions in key methane-emitting sectors – a GMP Energy Pathway launched at the June 2022 Major Economies Forum on Energy and Climate and a GMP Food and Agriculture Pathway and GMP Waste Pathway, both launched today at COP27.").

[177] United States Department of State (17 November 2022) *Global Methane Pledge: From Moment to Momentum*, Press Release ("The Global Methane Hub announced raising $70 million in support for a new Enteric Methane Research and Development Accelerator to advance critical research on reducing methane emissions from enteric fermentation—the largest single source of methane emissions from agriculture—and has a $200 million fundraising goal by the first quarter of 2023.").

[178] Global Methane Pledge (13 November 2024) *Factsheet: 2024 Global Methane Pledge Ministerial*, Press Release ("The U.S. Agency for International Development (USAID), through the $22.15 million State Department-funded Methane Accelerator, is reducing methane emissions while improving development outcomes across the energy, waste, and agriculture sectors, and has funded methane abatement work in Haiti, Indonesia, Kenya, Mexico, Philippines, Tanzania, Thailand, and Vietnam.").

[179] United States Department of State (12 November 2024) *The Sprint to Cut Climate Super Pollutants: COP 29 Summit on Methane and Non-CO_2 GHGs*, Fact Sheet ("The United States, People's Republic of China, and Azerbaijan today convened a Summit to accelerate actions to cut emissions of methane and other non-CO_2 greenhouse gases, which account for half of today's climate change but receive far less than half of global climate attention. These super pollutant greenhouse gases—including methane, hydrofluorocarbons, nitrous oxide, and tropospheric ozone—are dozens, hundreds, or even thousands of times more potent than carbon dioxide. Reducing emissions of these super pollutants is the fastest way to tackle climate change and a critical complement to reducing carbon dioxide to limit global warming to 1.5 degrees Celsius.").

[180] United States Department of State (12 November 2024) *The Sprint to Cut Climate Super Pollutants: COP 29 Summit on Methane and Non-CO_2 GHGs*, Fact Sheet ("***This year, partners announced:*** **Finance:** Over $2 billion in total international grant funding mobilized in the last three years to tackle super pollutants, and billions in additional investment deployed. **Policy:** New policy and regulatory steps to reduce methane emissions in the oil and gas and landfill sectors including by five of the top 20 waste sector methane emitters. **Science:** The launch of the first-ever Global Nitrous Oxide Assessment, which demonstrates that global N_2O emissions can be reduced by 40 percent, and new efforts to track and reduce the climate impacts of tropospheric ozone, the third-largest contributor to climate change.").

[181] United States Department of State (2 December 2023) *Accelerating Fast Mitigation: Summit on Methane and Non-CO_2 Greenhouse Gases*, Fact Sheet ("The United States, People's Republic of China, and United Arab Emirates today convened a Summit to accelerate actions to cut methane and other non-CO_2 greenhouse gases as the fastest way to reduce near-term warming and keep a goal of limiting global average temperature increase to 1.5 degrees Celsius within reach. At the Summit, the United Arab Emirates announced a call to action for Parties to the Paris Agreement to submit 2035 nationally determined contributions that are economy-wide and cover all greenhouse gases, which is encouraged by the G20 Leaders Statement and echoes the U.S. and PRC commitments in the Sunnylands Statement. Governments, philanthropies, and the private sector joined together to announce an unprecedented over $1 billion in new grant funding for methane reduction mobilized since COP27, which more than triples current annual grant funding and will leverage billions in project investment. Governments also reiterated their recent agreement to the largest ever replenishment of the Montreal Multilateral Fund with $965 million in funding to support Kigali Amendment implementation and energy efficiency.").

[182] United States Department of State (14 November 2023) *Sunnylands Statement on Enhancing Cooperation to Address the Climate Crisis*, ("The two countries will implement their respective national methane action plans and intend to elaborate further measures, as appropriate. The two countries will immediately initiate technical working group cooperation on policy dialogue, technical solutions exchanges, and capacity building, building on their respective national methane action plans to develop their respective methane reduction actions/targets for inclusion in their 2035 NDCs and support each country's methane reduction/control progress. The two countries intend to cooperate on respective measures to manage nitrous oxide emissions. The two countries intend to work together under the Kigali Amendment to phase down HFCs and commit to ensure application of ambitious minimum efficiency standards for all cooling equipment manufactured.").

[183] *See* Inflation Reduction Act, Pub. L. No. 117-169, §21001, 60114 (2022); United States Senate (28 July 2022) *Summary of the Energy Security and Climate Change Investments in the Inflation Reduction Act of 2022*; *and* United States White House (2023) BUILDING A CLEAN ENERGY ECONOMY: *A GUIDEBOOK TO THE INFLATION REDUCTION ACT'S INVESTMENTS IN CLEAN ENERGY AND CLIMATE ACTION*, Version 2, 130 ("The Inflation Reduction provides $19 billion to the U.S. Department of Agriculture (USDA) to support farmers and ranchers in adopting and expanding climate-smart activities and systems."). For further information on what is in the 2022 Inflation Reduction Act, *see* Paris F., Parlapiano A., Sanger-Katz M., & Washington E. (13 August 2022, *updated* 16 August 2022) *A Detailed Picture of What's in the Democrats' Climate and Health Bill*, THE NEW YORK TIMES.

[184] *See* Inflation Reduction Act, Pub. L. No. 117-169, §21001, 60114 (2022); United States Senate (28 July 2022) *Summary of the Energy Security and Climate Change Investments in the Inflation Reduction Act of 2022*; *and* United States White House (2023) BUILDING A CLEAN ENERGY ECONOMY: *A GUIDEBOOK TO THE INFLATION REDUCTION ACT'S*

INVESTMENTS IN CLEAN ENERGY AND CLIMATE ACTION, Version 2, 68 ("$1.55 billion to cut methane pollution from oil and gas industry operations. EPA received $1.55 billion to provide financial and technical assistance to accelerate the reduction of methane and other greenhouse gas emissions from petroleum and natural gas systems by improving and deploying new equipment, supporting technological innovation, permanently shutting in and plugging wells, and other activities. In addition to these financial incentives, the Inflation Reduction Act imposes a waste emissions charge on facilities with methane emissions that exceed a certain threshold. This EPA program complements nearly $4.7 billion in the Bipartisan Infrastructure Law to plug and remediate orphaned oil and gas wells on Tribal, federal, state, and private lands."). For further information on what is in the 2022 Inflation Reduction Act, *see* Paris F., Parlapiano A., Sanger-Katz M., & Washington E. (13 August 2022, *updated* 16 August 2022) *A Detailed Picture of What's in the Democrats' Climate and Health Bill*, THE NEW YORK TIMES. For the finalized rule on methane emissions reporting requirements, *see* United States Environmental Protection Agency (6 May 2024) *Biden-Harris Administration Announces Final Rule to Cut Methane Emissions, Strengthen and Update Greenhouse Gas Emissions Reporting for the Oil and Gas Sector*, Press Release.

[185] *See* Inflation Reduction Act, Pub. L. No. 117-169, §21001, 60114 (2022); United States Senate (28 July 2022) *Summary of the Energy Security and Climate Change Investments in the Inflation Reduction Act of 2022*; *and* Ramseur J. L. (29 August 2022) *Inflation Reduction Act Methane Emissions Charge: In Brief*, Congressional Research Service Report #R47206 9 ("The methane emissions charge in IRA starts in calendar year 2024 at $900 per metric ton of methane, increases to $1,200 in 2025, and increases to $1,500 in 2026. The charge remains at $1,500 in subsequent years."). For further information on what is in the 2022 Inflation Reduction Act, *see* Paris F., Parlapiano A., Sanger-Katz M., & Washington E. (13 August 2022, *updated* 16 August 2022) *A Detailed Picture of What's in the Democrats' Climate and Health Bill*, THE NEW YORK TIMES. For information on the finalized methane (waste emissions charge) fee, *see* United States Environmental Protection Agency (12 November 2024) *EPA Finalizes Rule to Reduce Wasteful Methane Emissions and Drive Innovation in the Oil and Gas Sector*, Press Release.

[186] Analyses by Princeton's REPEAT Project, Energy Innovation, and the Rhodium Group confirm the 40% GHG reductions capability of the 2022 Inflation Reduction Act. *See* Jenkins J. D., Mayfield E. N., Farbes J., Jones R., Patankar N., Xu Q., & Schivley G. (August 2022) *Preliminary Report: The Climate and Energy Impacts of the Inflation Reduction Act of 2022*, REPEAT Project, Princeton University ZERO Lab, 6 (Figure. Historical and Modeled Net U.S. Greenhouse Gas Emissions (Including Land Sinks); Mahajan M., Ashmoore O., Rissman J., Orvis R., & Gopal A. (August 2022) *Modeling the Inflation Reduction Act Using the Energy Policy Simulator*, Energy Innovation, 1 ("We find that the IRA is the most significant federal climate and clean energy legislation in U.S. history, and its provisions could cut greenhouse gas (GHG) emissions 37-41 percent below 2005 levels. If the IRA passes, additional executive and state actions can realistically achieve the U.S. nationally determined commitments (NDCs) under the Paris Agreement."); *and* Larsen J., King B., Kolus H., Dasari N., Hiltbrand G., & Herndon W. (12 August 2022) *A Turning Point for US Climate Progress: Assessing the Climate and Clean Energy Provisions in the Inflation Reduction Act*, The Rhodium Group ("The IRA is a game changer for US decarbonization. We find that the package as a whole drives US net GHG emissions down to 32-42% below 2005 levels in 2030, compared to 24-35% without it. The long-term, robust incentives and programs provide a decade of policy certainty for the clean energy industry to scale up across all corners of the US energy system to levels that the US has never seen before. The IRA also targets incentives toward emerging clean technologies that have seen little support to date. These incentives help reduce the green premium on clean fuels, clean hydrogen, carbon capture, direct air capture, and other technologies, potentially creating the market conditions to expand these nascent industries to the level needed to maintain momentum on decarbonization into the 2030s and beyond."), *discussed in* Hirji Z. (4 August 2022) *How the Senate's Big Climate Bill Eliminates 4 Billion Tons of Emissions*, BLOOMBERG.

[187] *See* Pub. L. No. 119-2 (*codified* Mar. 14, 2025); *discussed in* Quiñones M. (17 March 2025) *Trump signs resolutions to undo methane fee, offshore drilling rules*, E&E NEWS ("President Donald Trump on Friday signed legislation to scrap two Biden administration rules — one to reduce planet-warning methane emissions and the other affecting offshore drilling. Lawmakers acted under the Congressional Review Act, which allows Congress to overturn newly issued rules by simple majority. That bypasses the Senate filibuster. EPA's rule to implement a fee on methane leaks from the oil and gas industry is the first Biden action killed this year. Democrats mandated the fee in their 2022 climate law."). *See also* Environmental Protection Agency (17 March 2025) *Waste Emissions Charge* ("On March 14, 2025,

a joint Congressional resolution disapproved the 2024 Final Waste Emissions Charge Rule. This regulation no longer has any force of law and is not in effect[.]").

[188] Gordon D. (31 January 2025) *Three Reasons Why Confronting Methane Is the Key to Energy Security and a Stronger Economy*, RMI ("Stemming leakage solves numerous problems at once. More efficient operations produce less waste and save costly resources. Containing gas rather than leaking it bolsters energy security. Leak-free systems pose less danger to people and property. Given that methane superheats the planet, carefully containing gas means less damage and disruption from extreme weather events. Considering these opportunities together makes it clear that slashing methane is the key to our well-being. … Companies are openly certifying and selling low-leakage gas, creating high-paying jobs in oil field operations and maintenance. Since oil and gas assets are often located in remote areas, rural communities would likely see the greatest employment benefits. Adding to the economic growth spurred by job creation are policies that financially incentivize preventing methane leaks — spurring a wave of innovative technology development and installation. … Every molecule of methane that stays in a leak-free system improves efficiency and can help drive down costs for the end consumer while cutting energy waste. Stopping methane leaks also prevents the release of cancer-causing toxins like benzene that contaminate air, water, and soil, and put entire communities at risk."). *See also* Zaelke D. & Bledsoe P. (15 February 2025) *AI is the future of tech, but its effects on the climate could change everything*, THE HILL ("Plugging methane leaks also stops the waste of natural gas, saving money and aligning with President Trump's hydrocarbon emphasis.").

[189] United Nations Environment Programme & World Meteorological Organization (2011) INTEGRATED ASSESSMENT OF BLACK CARBON AND TROPOSPHERIC OZONE, 99–100 ("Similarly, the equilibrium warming from O_3 (forcing 0.3±0.15 W/m^2) would be 0.1 to 0.4ºC due to changes since pre-industrial times. The O_3 warming can be attributed to its precursor emissions. Applying a similar process to the O_3 precursor forcings from Figure 3.14 in Section 3.5 leads to an equilibrium warming of 0.1 to 0.3ºC due to the O_3 change from methane (CH_4) (0.5 to 1.2ºC total from CH_4 emissions), and much smaller contributions from the other O_3 precursors. All responses will be somewhat less due to the extent that the climate system has not fully adjusted to the forcings (i.e. the ocean can take decades to centuries to equilibrate with forcings), though as the global mean levels of several of these compounds appears to have levelled off during recent decades, unlike CO_2, a substantial portion of the adjustment has already taken place.").

[190] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS, 51–57 ("Long-term exposure to ozone can cause inflammation and allergic responses leading to respiratory mortality, as well as the development of a systemic oxidative, proinflammatory environment that can increase the risk of cardiovascular diseases. … It should be noted that the larger impact of ozone on health has been reported in several previous studies. Malley et al. (2017) used the new health exposure relationships (Turner et al. 2016) along with modelled ozone distributions, and found a 125 per cent increase in respiratory deaths attributable to ozone exposure in 2010 compared to previous estimates – 1.04–1.23 million deaths compared to 0.40–0.55 million. … Further to this, a bias-adjusted model recently reported total worldwide ozone-related premature deaths of 1.0 ± 0.3 million (Shindell et al. 2018). The value for respiratory-related premature deaths due to ozone was 0.6 ± 0.2 million for 2010, and 1.0 ± 0.3 million without bias adjustment, the latter being consistent with the value reported by Malley et al. (2017).").

[191] Feng Z., Xu Y., Kobayashi K., Dai L., Zhang T., Agathokleous E., Calatayud V., Paoletti E., Mukherjee A., Agrawal M., Park R. J., Oak Y. J., & Yue X. (2022) *Ozone pollution threatens the production of major staple crops in East Asia*, NAT. FOOD 3: 47–56, 47 ("East Asia is a hotspot of surface ozone (O_3) pollution, which hinders crop growth and reduces yields. Here, we assess the relative yield loss in rice, wheat and maize due to O_3 by combining O_3 elevation experiments across Asia and air monitoring at about 3,000 locations in China, Japan and Korea. China shows the highest relative yield loss at 33%, 23% and 9% for wheat, rice and maize, respectively. The relative yield loss is much greater in hybrid than inbred rice, being close to that for wheat. Total O_3-induced annual loss of crop production is estimated at US$63 billion."). *See also* United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS, 68 ("Methane also plays a significant role in reducing crop yields and the quality of vegetation. Ozone exposure is estimated to result in yield losses in wheat, 7.1 per cent; soybean,12.4 per cent; maize, 6.1 per cent; and rice, 4.4 per cent for near present-day global totals (Mills et al. 2018; Shindell et al. 2016; Avnery et al. 2011a)"); *and* Shindell D., Faluvegi G.,

Kasibhatla P., & Van Dingenen R. (2019) *Spatial Patterns of Crop Yield Change by Emitted Pollutant*, EARTH'S FUTURE 7(2): 101–112, 101 ("Our statistical modeling indicates that for the global mean, climate and composition changes have decreased wheat and maize yields substantially whereas rice yields have increased. Well-mixed greenhouse gasses drive most of the impacts, though aerosol-induced cooling can be important, particularly for more polluted area including India and China. Maize yield losses are most strongly attributable to methane emissions (via both temperature and ozone).").

[192] Mar K. A., Unger C., Walderdorff L., & Butler T. (2022) *Beyond* CO_2 *equivalence: The impacts of methane on climate, ecosystems, and health*, ENV. SCI. POL. 134: 127–136, 129 ("Methane is an important contributor to the formation of tropospheric O_3. In addition to acting as a greenhouse gas and being directly harmful to human health (see Section 3.3), it also harms plants by causing cellular damage within the leaves, adversely affecting plant production, reducing the rate of photosynthesis, and requiring increased resource allocation to detoxify and repair leaves (Ashmore, 2005, Sitch et al., 2007). This results in an estimated $11-$18 billion worth of global crop losses annually (Avnery et al., 2011). Beyond this, however, O_3 damage to plants may significantly reduce the ability of terrestrial ecosystems to absorb carbon, negating some of the enhanced carbon uptake due to CO_2 fertilization that is expected to partially offset rising atmospheric CO_2 concentrations (Sitch et al., 2007, Ciais et al., 2013, Arneth et al., 2010, Ainsworth et al., 2012)."). *See also* Szopa S., Naik V., Adhikary B., Artaxo P., Berntsen T., Collins W. D., Fuzzi S., Gallardo L., Kiendler-Scharr A., Klimont Z., Liao H., Unger N., & Zanis P. (2021) *Chapter 6: Short-lived climate forcers*, in CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 857 ("Ozone uptake itself damages photosynthesis and reduces plant growth with consequences for the carbon and water cycles (Ainsworth et al., 2012; Emberson et al., 2018).… Tropospheric aerosols influence the land and ocean ecosystem productivity and the carbon cycle through changing physical climate and meteorology (Jones, 2003; Cox et al., 2008; Mahowald, 2011; Unger et al., 2017) and through changing deposition of nutrients including nitrogen, sulphur, iron and phosphorous (Mahowald et al., 2017; Kanakidou et al., 2018). There is robust evidence and high agreement from field (Oliveira et al., 2007; Cirino et al., 2014; Rap et al., 2015; X. Wang et al., 2018) and modelling (Mercado et al., 2009; Strada and Unger, 2016; Lu et al., 2017; Yue et al., 2017) studies that aerosols affect plant productivity through increasing the diffuse fraction of downward shortwave radiation, although the magnitude and importance to the global land carbon sink is controversial. At large scales the dominant effect of aerosols on the carbon cycle is likely a global cooling effect of the climate (medium confidence) (Jones, 2003; Mahowald, 2011; Unger et al., 2017). We assess that these interactions between aerosols and the carbon cycle are currently too uncertain to constrain quantitatively the indirect CO_2 forcing. In summary, reactive nitrogen, ozone and aerosols affect terrestrial vegetation and the carbon cycle through deposition and effects on large-scale radiation (high confidence) but the magnitude of these effects on the land carbon sink, ecosystem productivity and indirect CO_2 forcing remain uncertain due to the difficulty in disentangling the complex interactions between the effects. As such, we assess the effects to be of second order in comparison to the direct CO_2 forcing (high confidence) but, at least for ozone, it could add a substantial (positive) forcing compared with its direct forcing (low confidence).").

[193] Butler T., Lupascu A., & Nalam A. (2020) *Attribution of ground-level ozone to anthropogenic and natural sources of nitrogen oxides and reactive carbon in a global chemical transport model*, ATMOS. CHEM. PHYS. 20(17): 10707–10731, 10726 ("As a reactive carbon precursor, methane contributes 35 % of the tropospheric ozone burden and 41 % of the Northern Hemisphere annual average surface mixing ratio, which is more than any other source of reactive carbon.").

[194] Intergovernmental Panel on Climate Change (2021) *Summary for Policymakers*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 27 ("Strong, rapid and sustained reductions in CH_4 emissions would also limit the warming effect resulting from declining aerosol pollution and would improve air quality."). *See also* Szopa S., Naik V., Adhikary B., Artaxo P., Berntsen T., Collins W. D., Fuzzi S., Gallardo L., Kiendler-Scharr A., Klimont Z., Liao H., Unger N., & Zanis P. (2021) *Chapter 6: Short-lived climate forcers*, in CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 821 ("Sustained methane mitigation, wherever it occurs, stands out as an option that combines near- and long-term gains on surface

temperature (*high confidence*) and leads to air quality benefits by reducing surface ozone levels globally (*high confidence*).").

[195] Mar K. A., Unger C., Walderdorff L. & Butler T. (2022) *Beyond* CO_2 *equivalence: The impacts of methane on climate, ecosystems, and health*, ENVT'L. SCIENCE & POL'Y 134: 127–136, 130 ("Importantly, the role of methane's contribution to O_3 production is expected to increase in the future, as emissions of other anthropogenic precursors (primarily NO_x and VOCs) are anticipated to decrease as a result of current and planned air quality regulations across much of the globe. For instance, Young et al. (2013) showed that rising CH_4 concentrations could be a major driver of increased surface O_3 by 2100 under the high-emission scenario developed for the IPCC 5th Assessment report. Turnock et al. (2018) showed that increased O_3 production from rising CH_4 concentrations could offset the reduction in surface O_3 due to reductions in emissions of shorter-lived O_3 precursors.").

[196] Protocol to the 1979 Convention on Long-range Transboundary Air Pollution to Abate Acidification, Eutrophication and Ground-level Ozone, 2319 U.N.T.S. 81 (2005).

[197] Smith S. J., McDuffie E. E., & Charles M. (2022) *Opinion: Coordinated development of emission inventories for climate forcers and air pollutants*, ATMOS. CHEM. PHYS. 22(19): 13201–13218, 13209 ("Tropospheric O_3 itself is also complex as it is both a health hazard and a GHG. While this means that reducing tropospheric O_3 on a global level is a "win–win" for both air pollution and climate, the impacts of O_3 occur across differing spatial and temporal scales. For air quality, most attention is focused on polluted areas with high seasonal and/or peak O_3 levels. In contrast, O_3 GHG forcing is not driven by areas of peak concentrations, but by the larger-scale background O_3 level. As mentioned above, local concentrations will largely depend on relative emissions of NO_x and NMVOC precursors, while background O_3 is determined largely by the magnitude of CH_4 and NO_x emissions."). *See also* Monks P. S., *et al.* (2015) *Tropospheric ozone and its precursors from the urban to the global scale from air quality to short-lived climate forcer*, ATMOS. CHEM. PHYS. 15(15): 8889–8973, 8901 ("While global average ozone responds to changes in global precursor emissions, trends at a given location are influenced by local, regional and global emission changes that may offset each other.").

[198] Monks P. S., *et al.* (2015) *Tropospheric ozone and its precursors from the urban to the global scale from air quality to short-lived climate forcer*, ATMOS. CHEM. PHYS. 15(15): 8889–8973, 8913 ("Moving to the urban scale, the local coupling of NO_x and O_3 is important in that reductions in NO can contribute to increases in ozone (Kley et al., 1994). In areas of high NO_x, as is often observed in urban areas, ozone levels can be suppressed through Reaction (R4). This phenomenon, sometimes dubbed "NO_x titration", thereby leads to the counterintuitive effect that reducing NO_x (NO) reduces the amount of ozone being suppressed and actually increases ozone (Heal et al., 2013; Sicard et al., 2013).").

[199] Amann M *et al.* (2020) *Reducing global air pollution: the scope for further policy interventions*, PHIL. TRANS. R. SOC. A 378: 3 ("Compared to the climate-focused analyses that deal mainly with energy-related emissions and the role of climate policy interventions, only a few studies addressed the longer-term prospects for air pollution from a health- and ecosystems perspective."); ("A comprehensive clean air policy that would also aim at ground-level ozone would need to include CH_4 and CO mitigation in its portfolio, especially in view of the past increases in hemispheric ozone levels that have been attributed to growing CH_4 emissions.").

[200] The Climate & Clean Air Coalition to Reduce Short-Lived Climate Pollutants (The CCAC identifies solutions to reduce SLCP emissions, conducts relevant scientific research, and promotes policy development. It is the only institution focusing solely on SLCP mitigation, although it does not have any regulatory authority.).

[201] Bond T. C., *et al.* (2013) *Bounding the role of black carbon in the climate system: A scientific assessment*, J. GEOPHYS. RES. ATMOS. 118(11): 5380–5552, 5420 ("Major sources of BC are also major sources of $PM_{2.5}$, but the converse is not always true; major sources of $PM_{2.5}$ may produce little BC if their emissions are primarily inorganic. Sources that are BC and OC emitters are shown in the table. Resuspended dust, secondary pollutants like sulfate and nitrate, or sea salt, could also be contributors to $PM_{2.5}$ at some locations but are not included in Table 11."); major sources in Table 11 include (in order of decreasing importance): transport (vehicle exhaust including gasoline and

diesel); IN = industry including coal and oil and biomass burning; coal burning power plants; RE = residential energy; OB= open burning of biomass and refuse; SA = secondary aerosols; O= Others.

[202] Lelieveld J., Klingmüller K., Pozzer A., Burnett R. T., Haines A., & Ramanathan V. (2019) *Effects of fossil fuel and total anthropogenic emission removal on public health and climate*, PROC. NAT'L. ACAD. SCI. 116(15): 7192–7197, 7193 ("We find that the global total excess mortality rate is 8.79 million per year, with a 95% confidence interval of 7.11–10.41 million per year."). *See also* Vohra K., Vodonos A., Schwartz J., Marais E. A., Sulprizio M. P., & Mickley L. J. (2021) *Global mortality from outdoor fine particle pollution generated by fossil fuel combustion: Results from GEOS-Chem*, ENVIRON. RES. 195: 1–33, 2 ("We used the chemical transport model GEOS-Chem to estimate global exposure levels to fossil-fuel related $PM_{2.5}$ in 2012. Relative risks of mortality were modeled using functions that link long-term exposure to $PM_{2.5}$ and mortality, incorporating nonlinearity in the concentration response. We estimate a global total of 10.2 (95% CI: -47.1 to 17.0) million premature deaths annually attributable to the fossil-fuel component of $PM_{2.5}$. The greatest mortality impact is estimated over regions with substantial fossil fuel related $PM_{2.5}$, notably China (3.9 million), India (2.5 million) and parts of eastern US, Europe and Southeast Asia. The estimate for China predates substantial decline in fossil fuel emissions and decreases to 2.4 million premature deaths due to 43.7% reduction in fossil fuel $PM_{2.5}$ from 2012 to 2018 bringing the global total to 8.7 (95% CI: -1.8 to 14.0) million premature deaths.").

[203] Clean Air Fund (2023) THE CASE FOR ACTION ON BLACK CARBON, 9 ("Assuming all components of $PM_{2.5}$ are equally toxic, outdoor/ambient black carbon exposure is estimated to be responsible for 150,000 excess deaths annually worldwide[24]; black carbon mitigation measures would also reduce co-emitted organic carbon, leading to as much as eight times more avoided deaths. These estimates are biased low since they do not include household air pollution. Residential biofuel use is a significant source of black carbon and a prime target for mitigation measures. Black carbon has been found to correlate more strongly than $PM_{2.5}$ with high blood pressure levels, contributing more to the burden of cardiovascular morbidity and mortality than other components of $PM_{2.5}$. As a result, the impact of black carbon reductions could be even higher. A recent study estimated that an 87% reduction of black carbon emissions over the Indo-Gangetic Plain alone could reduce premature mortality by as much as an estimated 400,000 lives annually.").

[204] United Nations Environment Programme & World Meteorological Organization (2011) INTEGRATED ASSESSMENT OF BLACK CARBON AND TROPOSPHERIC OZONE, 193, 201 ("Implementing all measures could avoid 2.4 million premature deaths (within a range of 0.7–4.6 million) associated with reductions in $PM_{2.5}$, associated with 5.3–37.4 million years of life lost (YLL), based on the 2030 population. … Total global production gains of all crops ranges between 30 and 140 million tonnes (model mean: 52 million tonnes). The annual economic gains for all four crops in all regions ranges between US$4billion and US$33 billion, of which US$2–28 billion in Asia.").

[205] Armstrong McKay D. I. & Loriani S. (eds.) (2023) *Section 1: Earth systems tipping points*, in GLOBAL TIPPING POINTS REPORT 2023, Lenton T. M., et al. (eds.), 9 ("Recommendations[:] Protect the cryosphere through urgent and ambitious phase-out of GHG emissions, as well as reducing co-drivers such as black carbon."). *See also* Milkoreit M. (ed.) (2023) *Section 3: Governance of Earth system tipping points*, in GLOBAL TIPPING POINTS REPORT 2023, Lenton T. M., et al. (eds.), 26 ("SLCPs, including methane, tropospheric ozone and black carbon, can have disproportionate regional impacts on particular tipping systems. For example, black carbon deposition is particularly effective at melting snow and ice. Hence the mitigation of specific SLCPs can have a disproportionate benefit in preventing specific ESTPs. Mitigating SLCPs can also contribute to limiting global warming pressure on most ESTPs. According to IPCC AR6 WG1, across the Shared Socioeconomic Pathway climate scenarios, "the collective reduction of methane, ozone precursors, and hydrofluorocarbons (HFCs) can make a difference of 0.2°C with a very likely range of [0.1 to 0.4]°C in 2040 and 0.8°C with a very likely range of [0.5 to 1.3]°C at the end of the 21st Century"."). *See also* Clean Air Fund (2023) THE CASE FOR ACTION ON BLACK CARBON, 6 ("Himalayan glacier retreat: • Near emission source – for example, domestic energy and brick kilns • The retreat of the Himalayan glaciers accelerated by 50% due to black carbon warming and snow darkening – this will have feedback effects on the Indian monsoon • Affects regional circulation and monsoon shift … Asian monsoon disruption • Northward shift of tropical rain clouds • Unseasonal extreme rainfall and disruptions in agriculture and livelihoods • Early onset also predicted due to black carbon emissions … West Africa monsoon shift • Decreased monsoon rainfall over West Africa and increased rainfall

over north-eastern Africa • Disruption to agriculture and ecosystems … Americas • Black carbon snow- and ice-darkening effects • Advanced melting over western United States[.]").

[206] Climate & Clean Air Coalition, *Black Carbon* (*last visited* 13 June 2023) (listing solutions to reach 70% reduction in black carbon by 2030).

[207] 1999 Protocol to Abate Acidification, Eutrophication and Ground-Level Ozone (Gothenburg Protocol), Decision 2012/8: Adoption of guidance document on control techniques for emissions of sulphur, nitrogen oxides, volatile organic compounds and particulate matter (including PM_{10}, $PM_{2.5}$, and black carbon) from stationary sources. *See also* Matthews B. & Paunu V.-V. (2019) *Review of Reporting Systems for National Black Carbon Emissions Inventories*, EU Action on Black Carbon in the Arctic - Technical Report 2, 1–2 ("Emissions reporting systems are thus in need of further improvement. In evaluating needs for improvement, the EU Action on Black Carbon in the Arctic review identified the following priority areas . . . 4. Enhanced cooperation between CLRTAP and the Arctic Council to expand and harmonise black carbon emissions reporting by countries whose black carbon emissions impact the Arctic."). *Compare with* Expert Group on Black Carbon and Methane (2019) *Summary of Progress and Recommendations*, Arctic Council Secretariat, 32 (Table 5, *showing* U.S. with 9.5bcm of flaring based on World Bank satellite observations); *and* Energy Information Administration, *Natural Gas Gross Withdrawals and Production* (*last visited* 10 June 2023) (showing combined flaring and venting volumes of 255bcm for 2017).

[208] World Bank (2014) REDUCING BLACK CARBON EMISSIONS FROM DIESEL VEHICLES: IMPACTS, CONTROL STRATEGIES, AND COST-BENEFIT ANALYSIS, 17 ("A vehicle emissions reduction program often focuses on three areas: new vehicles, fuels, and the in- use fleet. In some countries it may make sense to start with the in-use fleet and transportation demand management. In certain cases, fiscal policies can be effective tools to complement mandatory regulatory requirements. The order or priority in approach should be dictated by the baseline technology, the rate of growth of the fleet, the feasibility of available options, the institutional capacity to support the intervention, and other local considerations. Successful strategies tend to take a holistic approach that integrates all maximum feasible and cost-effective emissions reduction strategies."). *See also* Bond T. C., *et al.* (2013) *Bounding the role of black carbon in the climate system: A scientific assessment*, J. GEOPHYS. RES. ATMOS. 118(11): 5380–5552, 5525 ("Diesel sources of BC appear to offer the most promising mitigation opportunities in terms of near-term forcing and maturity of technology and delivery programs. Although some options, such as diesel retrofits, may be costly relative to other BC mitigation options, they may also deliver significant health benefits. Mitigating emissions from residential solid fuels may yield a reduction in net positive forcing. The near-term net effect remains uncertain because of uncertain knowledge regarding the impacts of co-emitted species on clouds, but longer-term forcing by co-emitted species interacting with the methane budget is positive. Furthermore, the evolution of feasibility is still in the emerging phase for these sources.").

[209] Clean Air Task Force, *Oil and Gas Mitigation Program* (*last visited* 13 June 2023) ("Operators often vent and flare natural gas at oil wells. This waste occurs when oil producers, driven by the rush to Operators often vent and flare natural gas at oil wells. This waste occurs when oil producers, driven by the rush to sell oil, simply dispose of the gas from producing oil wells instead of building infrastructure (such as pipelines) to capture gas as soon as production begins. (In some cases, pipelines are never built and all of the gas the well produces over its lifetime is wasted in this way, as can be seen in sales records for individual wells available from state regulators.) While a substantial portion of this gas is flared off — wasting energy and producing large amounts of carbon dioxide and other pollutants — some is just dumped into the air, or vented. Even in cases where a gas pipeline is not connected, there are a variety of other technologies that operators can use to reduce associated gas flaring at oil wells. Venting is even more harmful than flaring, since methane warms the climate so powerfully, and VOC and toxic pollutants are released unabated. Venting of this gas should be prohibited in all cases as an absolutely unnecessary source of harmful air pollution. There are numerous lowcost (and usually profitable) ways to utilize natural gas from oil wells. Flaring should be a last resort: only in the most extreme cases should oil producers be allowed to flare gas, and it should be strictly a temporary measure. Rules prohibiting venting of natural gas can easily reduce emissions by 95%."). *See also* World Bank, *Zero Routine Flaring by 2030 Initiative Text* (*last visited* 13 June 2023) ("This "**Zero Routine Flaring by 2030" initiative** (the Initiative), introduced by the World Bank, brings together governments, oil companies, and development institutions who recognize the flaring situation described above is unsustainable from a resource

management and environmental perspective, and who agree to cooperate to eliminate routine flaring no later than 2030."); *and* Saunier S., Bergauer M-A., & Isakova I. (2019) *Best Available Techniques Economically Achievable to Address Black Carbon from Gas Flaring*, EU Action on Black Carbon in the Arctic Technical Report 3, 3 ("Although the effectiveness of BATEA largely depends on site-specific economic and technical parameters, they have a substantial potential to achieve meaningful and measurable environmental and financial benefits. Quantifying resultant reductions in BC emissions as a result of mitigation strategies remains challenging, however, implementing BATEA should still be considered a best practice for reducing flaring-associated BC emissions. Along with other newly available technologies, use of the BATEA described herein will support existing efforts to mitigate short-term climate change, as well as address other energy, environmental, and safety issues that are likely to result from gas flaring in Arctic regions.").

[210] International Energy Agency, International Renewable Energy Agency, United Nations Statistics Division, World Bank, & World Health Organization (2020) TRACKING SDG 7: THE ENERGY PROGRESS REPORT, 6 ("The share of the global population with access to clean fuels and technologies for cooking increased from 56 percent in 2010 (uncertainty interval 52–61 percent) to 63 percent in 2018 (56–68), leaving approximately 2.8 billion people without access.[1] That number has been largely unchanged over the past two decades owing to population growth outpacing the number of people gaining access to clean cooking solutions."). Cleaner cookstoves must also be reliable for interventions to succeed: *see* Ramanathan T., Molin Valdés H., & Coldrey O. (7 September 2020) *Reliability matters: Achieving affordable, reliable, sustainable and modern energy for all by 2030*, SUSTAINABLE ENERGY FOR ALL ("A cooking solution (improved biomass, gas, electric, etc.) is reliable when it offers a household the predictable ability to cleanly cook essential foods on a daily basis and to continue to do so into the foreseeable future. Reliability is a holistic concept that encompasses not only the verifiability of emissions reduction, but also accounts for end users' needs (e.g. usability of design, long-term durability, affordability, and strength of supply chain). Compromising any of those factors can mean that even if a cooking solution is perceived as beneficial, it may not be well suited and will therefore ultimately not meet its targeted goal of cleaner air.").

[211] Comer B., Osipova L., Georgeff E., & Mao X. (2020) *The International Maritime Organization's proposed arctic heavy fuel oil ban: likely impacts and opportunities for improvement*, International Council on Clean Transportation, 1 ("In February 2020, delegates at the seventh session of the United Nations International Maritime Organization's (IMO) Pollution Prevention and Response Sub-Committee (PPR 7) agreed on draft amendments to the International Convention for the Prevention of Pollution from Ships (MARPOL) that would ban the carriage and use of heavy fuel oil (HFO) as fuel in Arctic waters beginning on July 1, 2024 (IMO Secretariat, 2020). If it were comprehensive, such a ban would dramatically reduce the potential for HFO spills and, in the likely cases where ships that stop using HFO switch to distillates, reduce the amount of black carbon (BC) they emit (Comer, Olmer, Mao, Roy, & Rutherford, 2017a). However, the text of the ban as currently proposed includes exemptions and waivers that would allow HFO to be carried and used in the Arctic until 2029. As proposed, the ban would enter into force for some ships on July 1, 2024, and implementation would be delayed for others. Ships with certain fuel tank protections, where the fuel tank is separated from the outer hull of the ship by at least 76 centimeters (cm), would be exempt until July 1, 2029. Additionally, countries with a coastline that borders IMO's definition of Arctic waters can waive the HFO ban's requirements until July 1, 2029 for ships that fly their flag when those ships are in waters subject to their sovereignty or jurisdiction."). *See also* Farand C. (3 September 2020) *Loopholes in Arctic heavy fuel oil ban defer action to the end of the decade*, CLIMATE HOME NEWS ("Under draft plans being negotiated at the International Maritime Organisation (IMO) – the UN body responsible for international shipping – restrictions on heavy fuel oil (HFO), a dirty fuel which propels most of marine transport, would come into effect in July 2024. But a host of exemptions and waivers would allow most ships using and carrying HFO to continue to pollute Arctic waters until 2029.").

[212] Arctic Council Expert Group on Black Carbon and Methane (2021) 3RD SUMMARY OF PROGRESS AND RECOMMENDATIONS, 15 ("Using the available emission estimates, Arctic States have collectively reduced their black carbon emissions by 20% in 2018, compared to 2013, and are projected to achieve a 32% decrease by 2025 (Table 1, Figure 1). Therefore, nationally reported emissions projections indicate that Arctic States are on track to achieve the aspirational collective goal to reduce black carbon emissions by 25-33% of 2013 levels by 2025."; Table 1 shows the projected combined emissions change for all Arctic Council countries from 2013 to 2025 as a 32% decrease, with the Russian Federation emissions have decreased by only 6%).

[213] Organisation for Economic Cooperation and Development (2021) THE ECONOMIC BENEFITS OF AIR QUALITY IMPROVEMENTS IN ARCTIC COUNCIL COUNTRIES, 13 (“Additional policies to extensively adopt the best available techniques would allow Arctic Council countries to reduce their emissions more substantially and halve their black carbon emissions by 2025, exceeding their collective target.”).

[214] Clean Air Fund (2023) THE CASE FOR ACTION ON BLACK CARBON, 21 (“All countries must commit to new, additional controls on black carbon emissions with concrete action plans that will result in measurable emission reductions as quickly as possible. As black carbon reductions have such fast-acting impacts on the climate system and air quality, speed of implementation must be the essential metric. All countries should include black carbon in their 2025 NDCs in a way that reduces black carbon emissions beyond what would be achieved with decarbonisation and methane mitigation actions alone. This approach will demonstrate the Paris Agreement principle of climate action done in the context of sustainable development and poverty eradication. Countries should (1) prioritise deep decarbonisation of black carbon-rich sources such as brick kilns, diesel engines and kerosene lamps; (2) support community-led forest fire management and (3) promote black carbon-free alternatives to residential biofuel use through policies, regulations, monitoring and funding measures. Countries of the Arctic Council should resume and enhance the ambition they have already demonstrated in addressing black carbon with an aggressive post-2025 black carbon reduction target. The Arctic Council should also engage with all observer countries and “observer-aspirant” countries to commit to a complementary black carbon target, individually or collectively. Countries should develop integrated greenhouse gas and air pollutant inventories and include short-lived climate forcers in their national inventory reports to the UNFCCC. Leadership organisations in other cryosphere regions, such as the Association of Southeast Asian Nations (ASEAN), Economic and Social Commission for Asia and the Pacific (ESCAP) and ICIMOD, should adopt and adapt the Arctic Council approach to collectively reduce black carbon emissions and drive climate and health benefits for their region. Countries should engage and support subnational jurisdictions in their efforts, particularly cities as they are concentrated sources of black carbon impacts and solutions. … The aforementioned black carbon reduction efforts should be supported by donor countries, multilateral development banks (MDBs) and philanthropic foundations through grants and concessional development financing so that recipient countries do not suffer debt distress as in the past. Donor countries funding decarbonisation efforts under Article 6.2 or other bilateral agreements should prioritise projects that simultaneously have the greatest potential to reduce black carbon emissions. MDBs should scale up financing for air quality programmes that target black carbon-rich sectors, expand GHG accounting to include all short-lived climate pollutants (SLCPs) for ongoing and new projects and engage with the Green Climate Fund to explicitly include black carbon in their finance instruments. Adaptation finance can open a new avenue of resourcing for black carbon reductions, with a type of finance that is more grant-based. Philanthropies should engage with the World Bank, the Global Environment Facility and regional MDBs to integrate black carbon into their programming and operations. They can support Non Governmental Organisations to develop awareness campaigns, build capacity for black carbon reduction efforts and develop sector-specific or city-specific black carbon mitigation plans. Critically, philanthropies can fill gaps in financing for mitigation actions where market forces or other financing mechanisms are insufficient or unlikely to reach.”); 4 (“National governments must include black carbon targets and additional actions to achieve them in their revised nationally determined contributions (NDCs). Nations can exhibit increased ambition in the 2025 global stocktake, demonstrate the Paris Agreement principle of climate action done in the context of sustainable development and poverty eradication and gain access to both mitigation and adaptation financing.”).

[215] Velders G. J. M., Andersen S. O., Daniel J. S., Fahey D. W., & McFarland M. (2007) *The importance of the Montreal Protocol in protecting climate*, PROC. NAT’L. ACAD. SCI. 104(12): 4814–4819, 4816 (“In contrast, without the early warning of the effects of CFCs (MR74 scenario), estimated ODS emissions would have reached 24–76 $GtCO_2$-eq yr 1 in 2010. Thus, in the current decade, in a world without ODS restrictions, annual ODS emissions using only the GWP metric could be as important for climate forcing as those of CO_2.”). *See also* Sigmond M., Polvani L. M., Fyfe J. C., Smith C. J., Cole J. N. S., & England M. R. (2023) *Large Contribution of Ozone-Depleting Substances to Global and Arctic Warming in the Late 20th Century*, GEOPHYS. RES. LETT. 50(5): 1–9, 4, 5 (“Furthermore, we place the warming from ODSs in the broader context of the total anthropogenic warming (which includes well mixed GHGs and ozone, and excludes the cooling effects of aerosols, see the previous section). The warming from all anthropogenic forcings (labeled “AntW” in Figure 2) is found to be 1.26°C in the ensemble mean.

ODSs, therefore, have contributed nearly one third (30%) of the total anthropogenic warming over the 1955 to 2005 period. … This second key result of our study, the high efficacy of ODSs, stands in contrast to the result obtained from highly idealized equilibrium forcing experiments (Richardson et al., 2019), which have reported an efficacy for CFC11 and CFC12 close to unity. Analyzing the realistic transient evolution of historical forcings over the 1955–2005 period, our model shows that ODSs are almost 20% more effective at warming global temperatures than carbon dioxide.”).

[216] Western L. M., *et al.* (2024) *A decrease in radiative forcing and equivalent effective chlorine from hydrochlorofluorocarbons*, NAT. CLIM. CHANG.: 1–7, 1, 2 (“Here we show that the radiative forcing and equivalent effective chlorine from hydrochlorofluorocarbons has decreased from 61.75 mW m^{-2} and 321.69 ppt, respectively, since 2021, 5 years before the most recent projected decrease.”; “The drop in radiative forcing and EECl was largely due to the atmospheric decline of the most abundant HCFC, HCFC-22, from its peak abundance of 248.96 ± 0.26 ppt in 2021 to 247.33 ± 0.32 ppt in 2023 (Extended Data Fig. 1). … “The timing of the apparent peak in HCFC radiative forcing and EECl is 5 years earlier than a previously projected maximum radiative forcing of 62.90 mW m−2 and EECl of 328.08 ppt in 2026 (based on HCFC-22, HCFC-141b and HCFC-142b only)[11].”).

[217] England M. R. & Polvani L. M. (2023) *The Montreal Protocol is delaying the occurrence of the first ice-free Arctic summer*, PROC. NAT’L. ACAD. SCI. 120(22): 1–7, 1 (“Current projections indicate that the first ice-free Arctic summer will likely occur by mid-century, owing to increasing carbon dioxide concentrations in the atmosphere. However, other powerful greenhouse gases have also contributed to Arctic sea ice loss, notably ozone-depleting substances (ODSs). In the late 1980s ODSs became strictly regulated by the Montreal Protocol, and their atmospheric concentrations have been declining since the mid-1990s. Here, analyzing new climate model simulations, we demonstrate that the Montreal Protocol, designed to protect the ozone layer, is delaying the first appearance of an ice-free Arctic summer, by up to 15 years, depending on future emissions. We also show that this important climate mitigation stems entirely from the reduced greenhouse gas warming from the regulated ODSs, with the avoided stratospheric ozone losses playing no role. Finally, we estimate that each Gg of averted ODS emissions results in approximately 7 km^2 of avoided Arctic sea ice loss.”).

[218] Garny H,. *et al.* (2022) *Chapter 5: Stratospheric Ozone Changes and Climate*, *in* SCIENTIFIC ASSESSMENT OF OZONE DEPLETION: 2022, Global Ozone Research and Monitoring Project–Report No. 278, World Meteorological Organization, United Nations Environment Programme, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, & European Commission, 310 (“The comparison of historical and RCP scenario integrations to world-avoided integrations provides an estimate of the impact of the Montreal Protocol on surface climate over the past several decades. Based on model simulations from three studies (Young et al., 2021; Goyal et al., 2019; Virgin and Smith, 2019), we assess that controls on ODS emissions under the Montreal Protocol have avoided at present-day (average over years 2015–2024) approximately 0.1– 0.2°C global surface warming (with an ensemble weighted mean of 0.17°C ± 0.06°C[2]) and 0.2– 0.6°C Arctic surface warming (ensemble weighted mean of 0.45°C ± 0.23°C). Using additional integrations with only world-avoided changes in stratospheric ozone included, the avoided warming is attributed primarily to the stabilization and slight decrease in ODS concentrations and is offset somewhat by cooling due to stratospheric ozone loss (Goyal et al., 2019; consistent with Section 5.3.1.1 and Box 5-3)…. As in previous Assessments, world-avoided integrations are also used to quantify avoided future climate change. While there has been limited new literature on the topic since the previous Assessment, based on three new studies (Goyal et al., 2019; Virgin and Smith, 2019; Young et al., 2021) we assess that by the mid-21st century (average over years 2041–2060) the Montreal Protocol controls would result in the avoidance of approximately 0.5–1.0°C global surface warming (ensemble weighted mean of 0.79°C ± 0.24°C). The globally averaged RF from the years 2005–2065 is approximately double in world-avoided scenarios due to uncontrolled emissions of ODSs compared to the RCP4.5 scenario (Virgin and Smith, 2019). This work supports findings of previous studies that compared the world-avoided scenario to the A1B and B2 SRES scenarios (Velders et al., 2007) or the RCP4.5 scenario (Garcia et al., 2012). Avoided Arctic warming is primarily due to reductions in ODS emissions rather than the mitigation of stratospheric ozone loss (Goyal et al., 2019; see also Section 5.3.1.2); however, recent work suggests that the relationship between Arctic warming and polar cap-averaged radiative forcing in the world-avoided scenario appears to be complex due to the unique combination of high ODS concentrations and substantial stratospheric ozone loss (Virgin and Smith, 2019). Arctic polar cap-averaged positive radiative feedbacks (i.e., long-wave cloud feedbacks) and atmospheric heat flux

convergence rather than polar cap-averaged radiative forcing alone play a key role in contributing to world-avoided Arctic warming (Virgin and Smith, 2019).").

[219] Young P. J., Harper A. B., Huntingford C., Paul N. D., Morgenstern O., Newman P. A., Oman L. D., Madronich S., & Garcia R. R. (2021) *The Montreal Protocol protects the terrestrial carbon sink*, NATURE 596(7872): 384–388, 384 ("Overall, at the end of the century, worldAvd warms by an additional 2.5 K (2.4–2.7 K) above the RCP 6.0 baseline in worldProj. Of this warming, 1.7 K comes from the previously explored[19] additional radiative forcing due to the higher CFC concentrations in worldProj."). *See also* United Nations Environment Programme, Ozone Secretariat (16 September 2022) *World Ozone Day 2022: Global cooperation protecting life on Earth* ("This action has protected millions of people from skin cancer and cataracts over the years since. It allowed vital ecosystems to survive and thrive. It safeguarded life on Earth. And it slowed climate change: if ozone-depleting chemicals had not been banned, we would be looking at a global temperature rise of an additional 2.5°C by the end of this century. This would have been a catastrophe."); World Meteorological Organization, United Nations Environment Programme, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, & European Commission (2022) SCIENTIFIC ASSESSMENT OF OZONE DEPLETION: 2022, Global Ozone Research and Monitoring Project–Report No. 278, WMO, 26 ("New studies support previous Assessments in that the decline in ODS emissions due to compliance with the Montreal Protocol avoids global warming of approximately 0.5–1 °C by mid-century compared to an extreme scenario with an uncontrolled increase in ODSs of 3–3.5% per year."); *and* Andersen S. O., Gonzalez M., & Sherman N. J. (18 October 2022) *Setting the stage for climate action under the Montreal Protocol*, EOS 103.

[220] Young P. J., Harper A. B., Huntingford C., Paul N. D., Morgenstern O., Newman P. A., Oman L. D., Madronich S., & Garcia R. R. (2021) *The Montreal Protocol protects the terrestrial carbon sink*, NATURE 596(7872): 384–388, 384 ("Newly quantified here is the additional warming of global-mean air temperature of 0.85 K (0.65–1.0 K)—half as much again—that arises from the higher atmospheric CO_2 concentrations due to the damaging effect of UV radiation on terrestrial carbon stores."). *See also* Garny H., *et al.* (2022) *Chapter 5: Stratospheric Ozone Changes and Climate*, *in* SCIENTIFIC ASSESSMENT OF OZONE DEPLETION: 2022, Global Ozone Research and Monitoring Project–Report No. 278, World Meteorological Organization, United Nations Environment Programme, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, & European Commission, 311 (""Using output from world-avoided simulations, it is estimated that atmospheric carbon dioxide concentrations may have been 18–37% higher by 2100 (Figure 5-19a) if controls on ODS emissions under the Montreal Protocol had not protected the terrestrial biosphere from UV damage, contributing to an additional 0.5–1.0 K to globally averaged surface warming by 2100 (Figure 5-19b). The large range of estimates reflects the uncertainty in the plant response to UV.").

[221] World Meteorological Organization, United Nations Environment Programme, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, & European Commission (2022) SCIENTIFIC ASSESSMENT OF OZONE DEPLETION: 2022, Global Ozone Research and Monitoring Project–Report No. 278, WMO, 3 ("TCO [total column ozone] is expected to return to 1980 values around 2066 in the Antarctic, around 2045 in the Arctic, and around 2040 for the near-global average (60°N–60°S). The assessment of the depletion of TCO in regions around the globe from 1980–1996 remains essentially unchanged since the 2018 Assessment.").

[222] England M. R. & Polvani L. M. (2023) *The Montreal Protocol is delaying the occurrence of the first ice-free Arctic summer*, PROC. NAT'L. ACAD. SCI. 120(22): e2211432120, 1 ("Current projections indicate that the first ice-free Arctic summer will likely occur by mid-century, owing to increasing carbon dioxide concentrations in the atmosphere. However, other powerful greenhouse gases have also contributed to Arctic sea ice loss, notably ozone-depleting substances (ODSs). In the late 1980s ODSs became strictly regulated by the Montreal Protocol, and their atmospheric concentrations have been declining since the mid-1990s. Here, analyzing new climate model simulations, we demonstrate that the Montreal Protocol, designed to protect the ozone layer, is delaying the first appearance of an ice-free Arctic summer, by up to 15 years, depending on future emissions. We also show that this important climate mitigation stems entirely from the reduced greenhouse gas warming from the regulated ODSs, with the avoided stratospheric ozone losses playing no role. Finally, we estimate that each Gg of averted ODS emissions results in approximately 7 km^2 of avoided Arctic sea ice loss."), *See also* Sigmond M., Polvani L. M., Fyfe J. C., Smith C. J.,

Cole J. N. S., & England M. R. (2023) *Large Contribution of Ozone-Depleting Substances to Global and Arctic Warming in the Late 20th Century*, GEOPHYS. RES. LETT. 50(5): 1–9, 4, 5 ("Furthermore, we place the warming from ODSs in the broader context of the total anthropogenic warming (which includes well mixed GHGs and ozone, and excludes the cooling effects of aerosols, see the previous section). The warming from all anthropogenic forcings (labeled "AntW" in Figure 2) is found to be 1.26°C in the ensemble mean. ODSs, therefore, have contributed nearly one third (30%) of the total anthropogenic warming over the 1955 to 2005 period. … This second key result of our study, the high efficacy of ODSs, stands in contrast to the result obtained from highly idealized equilibrium forcing experiments (Richardson et al., 2019), which have reported an efficacy for CFC11 and CFC12 close to unity. Analyzing the realistic transient evolution of historical forcings over the 1955–2005 period, our model shows that ODSs are almost 20% more effective at warming global temperatures than carbon dioxide.").

[223] Sigmond M., Polvani L. M., Fyfe J. C., Smith C. J., Cole J. N. S., & England M. R. (2023) *Large Contribution of Ozone-Depleting Substances to Global and Arctic Warming in the Late 20th Century*, GEOPHYS. RES. LETT. 50(5): 1–9, 5 ("Fixing ODSs to 1955 levels reduces 1955–2005 Arctic warming by 55% (45%–68%) and September sea ice extent decline by 45% (18%–67%), in good agreement with the values reported in Polvani et al. (2020). ODSs are found to be responsible for 1.15°C of the Arctic mean warming, which amounts to 66% of Arctic warming due to CO_2, and to 37% of the Arctic warming that is due to all anthropogenic warming agents. The ratio of Arctic relative to the global mean warming, referred to as Arctic amplification factor, is 2.99 (2.49–3.53) for ODSs, which is slightly larger than for CO_2 (2.78, 2.45–3.12), consistent with a previous study (Liang et al., 2022). However the difference is not statistically significant in our model. As for September sea ice extent, we find that ODSs are responsible for 0.82 million km^{2}of its decline, which is 33% of the decline due to all anthropogenic warming. In summary, more than a third of changes in key Arctic climate indicators between 1955 and 2005 can be attributed to ODS increases."). *See also* Polvani L. M., Previdi M., England M. R., Chiodo G., & Smith K. L. (2020) *Substantial twentieth-century Arctic warming caused by ozone-depleting substances*, NAT. CLIM. CHANG. 10(2): 130–133, 133 ("Without the large cancellation from aerosols the relative contribution of ODS to the total forced Arctic climate change would be smaller. However, irrespective of aerosols, the absolute contribution of ODS—nearly 0.8 °C of warming and 0.7×106 km^2 of September sea ice loss over only 50 years—is remarkably large. In conclusion, if our findings are confirmed by future studies, the role of the Montreal Protocol as a major environmental treaty will assume a new dimension. Our model integrations show that, in addition to being the key drivers of stratospheric ozone depletion (notably over the South Pole), ODS have been important players in the global climate system, notably in the Arctic, over the second half of the twentieth century. Our findings also have implications for the future because the phase-out of ODS, which is well under way, will substantially mitigate Arctic warming and sea-ice melting in the coming decades.").

[224] Andersen S. O., Gao S., Carvalho S., Ferris T., Gonzalez M., Sherman N. J., Wei Y., & Zaelke D. (2021) *Narrowing feedstock exemptions under the Montreal Protocol has multiple environmental benefits*, PROC. NAT'L. ACAD. SCI. 118(49): 1–10, 7 ("Reducing feedstock uses would reduce unlawful ODS and HFC production because there would be fewer facilities capable of producing these substances, which could then be more carefully monitored… It is not yet possible to accurately quantify the feedstock emissions (both absolute quantities and relative percentages) that can be avoided by narrowing the feedstock exemptions under the Montreal Protocol, primarily because of inaccurate and incomplete reporting of feedstock production and use. However, recent atmospheric monitoring suggests that the benefits of narrowing feedstock exemptions can be substantial. For example, 309 Tg CO_2-eq of HFC-23 emissions were added to the atmosphere between 2015 and 2017, roughly equivalent to the total GHG emissions of Spain in 2017 (71). Also, global emissions of high-GWP CFC-11, CFC-12, CFC-113, and HFC-23 (see Table 3) have all been elevated in the past few years beyond levels explained by legal production and de minimis feedstock emissions (67, 70, 71). As Solomon et al. pointed out, "so far, the added CFC-11 has not been enough to significantly delay the closing of the ozone hole, but continuing additions of CFC-11 beyond 2030 would impede successful healing of the ozone hole by a decade or more" (40).").

[225] Western L. M., *et al.* (2023) *Global increase of ozone-depleting chlorofluorocarbons from 2010 to 2020*, NAT. GEOSCI. 16: 309–313, 312 ("Combined global emissions of CFC-13, CFC-112a, CFC-113a, CFC-114a and CFC-115 increased from 1.6 ± 0.2 to 4.2 ± 0.4 ODP-Gg yr^{-1} (ODP-Gg, mass weighted by their CFC-11-equivalent ozone-depleting potential (ODP)) between 2010 and 2020 (Fig. 2). The mean growth rate of these emissions is around 0.3 ODP-Gg yr^{-1} per year. Global emissions of CFC-11 increased between the periods 2008–2012 and 2014–2018[5,19]

which were attributed to unreported production. The increase in global emissions between 2010 and 2020 of the five CFCs reported here (expressed as ODP-Gg yr^{-1}) is around a fifth of the global increase in CFC-11. In terms of impact on climate, the five CFC emissions derived for 2020 are equivalent to 47 ± 5 $TgCO_2$-equivalent (CO_2e) yr^{-1} in 2020 (around 150% of London's CO_2 emissions in 2018[20] based on 100 yr global warming potentials). … Ozone-depleting substances used as feedstocks and produced as by-products are not subject to the same controls on production as those for so-called dispersive use under the Montreal Protocol. As such, there is no current barrier to future use in the synthesis of chemicals. In the absence of further evidence, it is likely that the rapidly rising emissions of the long-lived ozone-depleting CFCs identified here are from processes not subject to current controls under the Montreal Protocol.").

[226] Xu Y., Zaelke D., Velders G. J. M., & Ramanathan V. (2013) *The role of HFCs in mitigating 21st century climate change*, ATMOS. CHEM. PHYS. 13(12): 6083–6089, 6083 ("Here we show that avoiding production and use of high-GWP (global warming potential) HFCs by using technologically feasible low-GWP substitutes to meet the increasing global demand can avoid as much as another 0.5 ºC warming by the end of the century. This combined mitigation on SLCPs would cut the cumulative warming since 2005 by 50% at 2050 and by 60% at 2100 from the CO_2-only mitigation scenarios, significantly reducing the rate of warming and lowering the probability of exceeding the 2 ºC warming threshold during this century."). For an updated assessment of HFC mitigation from policy adopted in the lead-up to the Kigali Amendment and locked-in with the entry into force of the Kigali Amendment, *see* Velders G. J. M., Daniel J. S., Montzka S. A., Vimont I., Rigby M., Krummel P. B., Muhle J., O'Doherty S., Prinn R. G., Weiss R. F., & Young D. (2022) *Projections of hydrofluorocarbon (HFC) emissions and the resulting global warming based on recent trends in observed abundances and current policies*, ATMOS. CHEM. PHYS. 22(9): 6087–6101, 6099 ("Projected mixing ratios, radiative forcing, and globally averaged temperature changes are calculated from the projected HFC emissions. The 2050 radiative forcing is 0.13–0.18 Wm^{-2} in the current policies K-I scenario and drops to 0.08–0.09 Wm^{-2} when the additional Kigali Amendment controls are considered (in KA-2022). In the current policies K-I scenario, the HFCs are projected to contribute 0.14–0.31 °C to the global surface warming in 2100, compared to 0.28–0.44 °C without policies. Following the Kigali Amendment, the surface warming of HFCs is reduced to about 0.05 °C in 2050 and 0.04 °C in 2100 (KA-2022. In a hypothetical scenario with a full phaseout of HFCs production and consumption in 2023, the contribution is reduced to about 0.01 °C in 2100."). *See also* World Meteorological Organization, United Nations Environment Programme, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, & European Commission (2022) SCIENTIFIC ASSESSMENT OF OZONE DEPLETION: 2022, Global Ozone Research and Monitoring Project–Report No. 278, WMO, 3 ("Compliance with the 2016 Kigali Amendment to the Montreal Protocol, which requires phase down of production and consumption of some hydrofluorocarbons (HFCs), is estimated to avoid 0.3–0.5 °C of warming by 2100. This estimate does not include contributions from HFC-23 emissions.").

[227] Montzka S. A., Velders G. J. M., Krummel P. B., Mühle J., Orkin,V. L., Park S., Shah N., & Walter-Terrinoni H. (2018) *Chapter 2: Hydrofluorocarbons (HFCs), in* SCIENTIFIC ASSESSMENT OF OZONE DEPLETION: 2018, Global Ozone Research and Monitoring Project–Report No. 58, World Meteorological Organization, United Nations Environment Programme, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, & European Commission, 2.40–2.41 ("With the Kigali Amendment and national and regional regulations, the future production and consumption of HFCs is strongly limited (Table 2-1). Under the provisions of the Amendment, the contribution of HFCs to the global average surface temperature is projected to reach a maximum around 2060, after which it slowly decreases to about 0.06°C by 2100 (Figure 2-20). In contrast, the surface temperature contribution from HFCs in the baseline scenario is 0.3–0.5°C in 2100 (based on Xu *et al.*, 2013 and Velders *et al.*, 2015). The difference in projected temperatures is relevant in the context of the 2015 UNFCCC Paris Agreement, which aims to limit the global temperature increase to well below 2°C relative to pre-industrial levels."). *See also* World Meteorological Organization, United Nations Environment Programme, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, & European Commission (2022) SCIENTIFIC ASSESSMENT OF OZONE DEPLETION: 2022, Global Ozone Research and Monitoring Project–Report No. 278, WMO, 21 ("Following the controls of the Kigali Amendment, HFC emissions (excluding HFC-23) in 2050 are projected to be 0.9–1.0 Gt CO_2-eq. yr^{-1} in the updated 2022 Kigali Amendment scenario, compared to 4.0–5.3 Gt CO_2eq yr^{-1} in the 2018 scenario without control measures (Figure ES-4). The corresponding radiative forcing in 2050 due to HFCs is 0.09–0.10 W m^{-2} with adherence to the Kigali Amendment, compared to 0.22–0.25 W m^{-2} without

control measures. Annual average surface warming from HFCs is expected to be 0.04 °C in 2100 under the updated 2022 Kigali Amendment scenario, compared to 0.3–0.5 °C without control measures."); *and* Liang Q., Rigby M., Fang X., Godwin D., Mühle J., Saito T., Stanley K. M., Velders G. J. M., Bernath P., Derek N., Reimann S., Simpson I. J., & Western L. (2022) *Chapter 2: Hydrofluorocarbons (HFCs)*, *in* SCIENTIFIC ASSESSMENT OF OZONE DEPLETION: 2022, Global Ozone Research and Monitoring Project–Report No. 278, World Meteorological Organization, United Nations Environment Programme, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, & European Commission, 143 ("In the new scenario following current trends, national policies, and the provisions of the Kigali Amendment, the HFCs are projected to contribute 0.04°C to the global average surface warming in 2100, compared to 0.3– 0.5°C in the baseline scenarios of the previous Assessment (Montzka, Velders et al., 2018; Velders et al., 2022). The updated Kigali Amendment scenario leads to a temperature rise that is slightly lower than that of the previous Assessment. For comparison, all greenhouse gases (GHGs) are projected to contribute 1.4–4.4°C to surface warming by the end of the 21st century, following the IPCC scenarios (best estimate for 2081–2100; IPCC, 2021). In hypothetical scenarios with a cease in global production or emissions of HFCs in 2023, the contribution to surface warming is reduced to no more than 0.01°C in 2100.").

[228] Liang Q., Rigby M., Fang X., Godwin D., Mühle J., Saito T., Stanley K. M., Velders G. J. M., Bernath P., Derek N., Reimann S., Simpson I. J., & Western L. (2022) *Chapter 2: Hydrofluorocarbons (HFCs)*, *in* SCIENTIFIC ASSESSMENT OF OZONE DEPLETION: 2022, Global Ozone Research and Monitoring Project–Report No. 278, World Meteorological Organization, United Nations Environment Programme, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, & European Commission, 145 (Figure 2-18 shows warming absent control measures on the order of 0.12°C compared with the updated Kigali scenario showing a warming of about 0.05°C). See also Szopa S., Naik V., Adhikary B., Artaxo P., Berntsen T., Collins W. D., Fuzzi S., Gallardo L., Kiendler-Scharr A., Klimont Z., Liao H., Unger N., & Zanis P. (2021) *Chapter 6: Short-lived Climate Forcers*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 873 ("Efficient implementation of the Kigali Amendment and national and regional regulations has been projected to reduce global average warming in 2050 by 0.05°C–0.07°C (Klimont et al., 2017b; WMO, 2018) and by 0.2°C–0.4°C in 2100 compared with the baseline (see Figure 2.20 of WMO, 2018). Analysis of SSP scenarios based on an emulator (Section 6.7.3) shows a comparable mitigation potential of about 0.02°C–0.07°C in 2050 and about 0.1°C–0.3°C in 2100 (Figure 6.22, SSP5-8.5 versus SSP1-2.6). Furthermore, the energy efficiency improvements of cooling equipment alongside the transition to low-global-warming potential alternative refrigerants for refrigeration and air-conditioning equipment could potentially increase the climate benefits from the HFC phasedown under the Kigali Amendment (Shah et al., 2015; Höglund-Isaksson et al., 2017; Purohit and Höglund-Isaksson, 2017; WMO, 2018). Purohit et al. (2020) estimated that depending on the expected rate of technological development, improving the energy efficiency of stationary cooling technologies and compliance with the Kigali Amendment could bring future global electricity savings of more than 20% of the world's expected electricity consumption beyond 2050 or cumulative reduction of about 75–275 Gt CO_2-eq over the period 2018–2100 (medium confidence). This could potentially double the climate benefits of the HFC phase-down of the Kigali Amendment as well as result in small air-quality improvements due to reduced air pollutant emissions from the power sector (i.e., 8–16% reduction of $PM_{2.5}$, SO_2 and NO_x; Purohit et al., 2020).").

[229] Purohit P., Borgford-Parnell N., Klimont Z., & Höglund-Isaksson L. (2022) *Achieving Paris climate goals calls for increasing ambition of the Kigali Amendment*, NAT. CLIM. CHANGE 12: 339–342, 339 ("Hydrofluorocarbon emissions have increased rapidly and are managed by the Kigali Amendment to the Montreal Protocol. Yet the current ambition is not consistent with the 1.5 °C Paris Agreement goal. Here, we draw on the Montreal Protocol start-and-strengthen approach to show that accelerated phase-down under the Kigali Amendment could result in additional reductions of 72% in 2050, increasing chances of staying below 1.5 °C throughout this century.").

[230] World Meteorological Organization, United Nations Environment Programme, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, & European Commission (2018) SCIENTIFIC ASSESSMENT OF OZONE DEPLETION: 2018, Global Ozone Research and Monitoring Project Report No. 58, World Meteorological Organization, ES-22, 2.40–2.41 ("The Kigali Amendment is projected to reduce future global average warming in 2100 due to HFCs from a baseline of 0.3-0.5 ºC to less than 0.1 ºC (Figure ES-4). If the global production

of HFCs were to cease in 2020, the surface temperature contribution of the HFC emissions would stay below 0.02 ºC for the whole 21st century. The magnitude of the avoided temperature increase, due to the provisions of the Kigali Amendment (0.2 to 0.4 ºC) is substantial in the context of the 2015 UNFCCC Paris Agreement, which aims to limit global temperature rise to well below 2.0 ºC above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 ºC. … With the Kigali Amendment and national and regional regulations, the future production and consumption of HFCs is strongly limited (Table 2-1). Under the provisions of the Amendment, the contribution of HFCs to the global average surface temperature is projected to reach a maximum around 2060, after which it slowly decreases to about 0.06°C by 2100 (Figure 2-20). In contrast, the surface temperature contribution from HFCs in the baseline scenario is 0.3–0.5°C in 2100 (based on Xu et al., 2013 and Velders et al., 2015). The difference in projected temperatures is relevant in the context of the 2015 UNFCCC Paris Agreement, which aims to limit the global temperature increase to well below 2°C relative to pre-industrial levels.").

[231] Theodoridi C., Hillbrand A., Starr C., Mahapatra A., & Taddonio K. (2022) *The 90 Billion Ton Opportunity: Lifecycle Refrigerant Management*, Environmental Investigation Agency, Institute for Governance & Sustainable Development, & Natural Resources Defense Council, 7 ("In the United States, minimizing leaks from refrigerators and air conditioners and ensuring the recovery, reclamation, and destruction of refrigerants at equipment end of life could avoid the atmospheric release of 9.2 billion metric tons of CO_2-equivalent ($GtCO_2e$) by 2100.[i] Globally, refrigerant management could avoid the gradual release of up to 91 $GtCO_2e$ this century — nearly three times global energy-related carbon dioxide emissions in 2019.[5]").

[232] World Meteorological Organization (2022) SCIENTIFIC ASSESSMENT OF OZONE DEPLETION: 2022, Global Ozone Research and Monitoring Project–Report No. 278, WMO, 3 ("Compliance with the 2016 Kigali Amendment to the Montreal Protocol, which requires phase down of production and consumption of some hydrofluorocarbons (HFCs), is estimated to avoid 0.3–0.5 °C of warming by 2100. This estimate does not include contributions from HFC-23 emissions."). *See also* Liang Q., Rigby M., Fang X., Godwin D., Mühle J., Saito T., Stanley K. M., Velders G. J. M., Bernath P., Derek N., Reimann S., Simpson I. J., & Western L. (2022) *Chapter 2: Hydrofluorocarbons (HFCs), in* SCIENTIFIC ASSESSMENT OF OZONE DEPLETION: 2022, Global Ozone Research and Monitoring Project–Report No. 278, World Meteorological Organization, 143 ("Under the business-as-usual scenario, if the current fractional rate of HFC-23 destruction continues into the future, radiative forcing due to HFC-23 is expected to reach 0.015 W m^{-2} in 2050. Under the scenario in which there is widespread destruction of HFC-23 by-product, the contribution of HFC-23 to overall HFC radiative forcing will be small (Section 7.2.2.1).").

[233] Rust D., Vollmer M. K., Henne S., Frumau A., van den Bulk P., Hensen A., Stanley K. M., Zenobi R., Emmenegger L., & Reimann S. (2024) *Effective realization of abatement measures can reduce HFC-23 emissions*, NATURE: 1–5, 3 ("Our inferred EF broadly fits with the "practicable" EF of 0.1% that is required to be achieved by abatement projects (with destruction) recently funded by the Multilateral Fund[5,6]. … To our knowledge, this study provides the first independent experimentally derived top-down-based evidence of practicable abatement. If this practice had been applied globally, and also accounting for HFC-23 emissions of 0.77 (0.37–1.9) Gg yr^{-1} from other sources than the production and processing of HCFC-22 (Methods), it would likely have resulted in an average HFC-23 abatement of 14 (12–16) Gg yr^{-1} for 2019–2020, corresponding to an 84% (69–100%) reduction of the HFC-23 emissions inferred from global observations[1]. This reduction is equivalent to 170 (150–200) Tg CO_2eq yr^{-1}, which compares with 17% of the carbon dioxide (CO2) emissions from pre-COVID-19 pandemic aviation (1,036 Tg CO_2 yr^{-1} for 2019)[7].").

[234] Staniaszek Z., Griffiths P. T., Folberth G. A., O'Connor F. M., Abraham N. L., & Archibald A. T. (2022) *The role of future anthropogenic methane emissions in air quality and climate*, NPJ CLIM. ATMOS. SCI. 5(1): 1–8, 1 ("HFC-23 (trifluoromethane) is a potent greenhouse gas released to the atmosphere primarily as a byproduct of HCFC-22 (chlorodifluoromethane) synthesis. Since 2020, the Kigali Amendment to the Montreal Protocol has required Parties to destroy their HFC-23 emissions to the extent possible. Here, we present updated HFC-23 emissions estimated from atmospheric observations. Globally, emissions fell to 14.0 ± 0.9 Gg yr-1 in 2023 from their maximum in 2019 of 17.3 ± 0.8 Gg yr-1, but remained five times higher than reported in 2021. Atmospheric observation-based emissions for eastern China, the world's largest HCFC-22 producer, were also found to be substantially higher than 2020-2022 reported emissions. We estimate that potential HFC-23 sources not directly linked to HCFC-22 production explain only a minor, albeit highly uncertain, fraction of this discrepancy. Our findings suggest that HFC-23 emissions have

not been destroyed to the extent reported by the Parties since the implementation of the Kigali Amendment."); 4 ("Although total global reported HCFC-22 production for combined feedstock and non-feedstock uses has increased by approximately 25% since 2015[9,21] (see Fig. 1b), such abatement of HFC-23 emissions from this process would be expected to lead to a substantial drop in emissions of HFC-23 globally. This expectation assumes that HCFC-22 production is the main source of these emissions, which previous work showed to be the case before the implementation of abatement policies[4,23]. Our analysis of other potential sources of HFC-23 suggests that, based on currently available information, this is likely to still be the case. The magnitude of reported abatement is such that the increase in the amount of HFC-23 generated through HCFC-22 production should be outweighed by the near-total abatement, resulting in far smaller amounts released to the atmosphere overall than in 2015. The trend in global emissions derived from atmospheric data does not reflect this expectation, as emissions increased every year from 2016–2019 despite the increase in reported abatement, and remained above 2015 levels in 2023. This trend is also found in eastern China, where top-down emissions for 2021–2023 (5.1 ± 0.6 Gg yr^{-1} on average) are very similar to those in 2015 (5.8 ± 0.6 Gg yr^{-1}), despite reported abatement increasing from 0% to 99.8% between these years. Therefore, if HCFC-22 production remains the dominant source of HFC-23 emissions in China, abatement levels must be lower than reported."). *See also* Montzka S.A., Burkholder J.B., Carpenter L.J., Fahey D.W., Jucks K.W., & Safari B. (2024) *Report of the Scientific Assessment Panel in response to Decision XXXV/7: Emissions of HFC-23*.

[235] Dreyfus G., Borgford-Parnell N., Christensen J., Fahey D. W., Motherway B., Peters T., Picolotti R., Shah N., & Xu Y. (2020) ASSESSMENT OF CLIMATE AND DEVELOPMENT BENEFITS OF EFFICIENT AND CLIMATE-FRIENDLY COOLING, Molina M. & Zaelke D., Steering Committee Co-Chairs, xii ("Transitioning to high efficiency cooling equipment can more than double the climate benefits of the HFC phasedown in the near-term by reducing emissions of carbon dioxide (CO_2) and black carbon from the electricity and diesel used to run air conditioners and other cooling equipment. This also will provide significant economic, health, and development co-benefits. … Robust policies to promote the use of best technologies currently available for efficient and climate-friendly cooling have the potential to reduce climate emissions from the stationary air conditioning and refrigeration sectors by 130–260 $GtCO_2e$ by 2050, and 210–460 $GtCO_2e$ by 2060. A quarter of this mitigation is from phasing down HFCs and switching to alternatives with low global warming potential (GWP), while three-quarters is from improving energy efficiency of cooling equipment and reducing electricity demand, which helps achieve a more rapid transition to carbon free electricity worldwide. The mobile air conditioning sector, where energy consumption is expected to nearly triple by 2050, offers significantly more mitigation potential."). *See also* Purohit P., Höglund-Isaksson L., Dulac J., Shah N., Wei M., Rafaj P., & Schöpp W. (2020) *Electricity savings and greenhouse gas emission reductions from global phase-down of hydrofluorocarbons*, ATMOS. CHEM. PHYS. 20(19): 11305–11327, 11305 ("The combined effect of HFC phase-down, energy efficiency improvement of the stationary cooling technologies, and future changes in the electricity generation fuel mix would prevent between 411 and 631 $PgCO_2$ equivalent of GHG emissions between 2018 and 2100, thereby making a significant contribution towards keeping the global temperature rise below 2 °C.").

[236] *Amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer*, 15 October 2016, C.N.872.2016.TREATIES-XXVII.2.f. *See also* United Nations Environmental Programme Ozone Secretariat, *Country Data* (*last accessed* 2 April 2025).

[237] United Nations Environmental Programme & Cool Coalition (2023) KEEPING IT CHILL: HOW TO MEET COOLING DEMANDS WHILE CUTTING EMISSIONS – GLOBAL COOLING WATCH 2023, xiv ("Based on current policies, between now and 2050 the installed capacity of cooling equipment globally will triple, resulting in a more than doubling of electricity consumption. This will lead emissions from cooling to surge to 6.1 billion tons of carbon dioxide equivalent (CO_2e) in 2050, equivalent to more than 10 per cent of global projected emissions that year."); 3 ("Cooling is already a significant contributor to peak power demand in many regions, and its growth will add further pressure on power grids, especially in developing countries (IEA n.d.). Key drivers that will affect these trends include: Climate change. The Intergovernmental Panel on Climate Change (IPCC) estimates that GHG emissions from human activities have contributed around 1.1 degrees Celsius (°C) of warming since 1850-1900, and that, averaged over the next 20 years, warming will reach or exceed a further 1.5°C (IPCC 2021). Africa, Latin America, South and East Asia, and the Middle East will see the largest absolute increase in "cooling degree days" as the planet warms – an indicator of the typical cooling required based on local weather conditions (Miranda et al. 2023). Population growth. More than 98 per cent of the population growth between 2022 and 2050 is expected to occur in developing countries, especially in

warmer climates (Population Reference Bureau [PRB] 2022; United Nations Department of Economic and Social Affairs [UN DESA] 2022). Africa, which has the highest rate of population growth among major world regions, is expected to account for more than half of global population growth between now and 2050, with the population of sub-Saharan Africa doubling in size (PRB 2022). Income growth. The global economy has expanded 35 per cent over the last decade (World Economics n.d.), leading to a rising middle class in many developing countries. For households that have growing incomes in hot countries, cooling is high on the list of "must-have" technologies to enable thermal comfort for well-being and productivity (Howarth et al. 2023).").

[238] United Nations Environmental Programme & Cool Coalition (2023) Keeping it Chill: How to meet cooling demands while cutting emissions – Global Cooling Watch 2023, xiv ("Meeting growing cooling demand sustainably presents one of the biggest opportunities to protect people, prosperity and the planet. 1 Calculated based on the Current Policies Scenario in the United Nations Environment Programme's (UNEP) 2023 Emissions Gap Report; see UNEP 2023a. Executive Summary Integrated action is needed in three key areas: 1) Passive strategies to address extreme heat and reduce cooling demand in buildings and in the cold chain. 2) Higher energy efficiency standards and norms for cooling equipment. 3) A phase down of climate-warming hydrofluorocarbon (HFC) refrigerants at a faster rate than is required under the Kigali Amendment to the Montreal Protocol, while improving the energy efficiency of cooling equipment.); xv ("Fully implementing the measures outlined in this report can: Reduce the 2050 greenhouse gas (GHG) emissions from cooling by at least 60 per cent (around 3.8 billion tons of CO_2e emissions), and this could increase to a 96 per cent reduction depending on rates of grid decarbonization. The cumulative savings, measured at a social cost of carbon of US$185 per ton of CO_2e, are US$16.5 trillion (2020 US$)."). *See also* Dreyfus G. & Horowitz N. (4 December 2023) *Investing in sustainable cooling to protect the planet*, Clean Cooling Collaborative ("Faced with "global boiling," more and more people will need access to sustainable cooling that doesn't further warm the planet. This means scaling passive cooling solutions and increasing access to affordable, energy-efficient, and climate-friendly air conditioning and refrigeration. Meeting this need requires transforming the air conditioning and refrigeration sectors. This is one reason that COP28 is being heralded as the "Cooling COP" and will feature the launch of the Global Cooling Pledge on December 5. Under the Kigali Amendment agreed to in 2016, the Montreal Protocol is now working to enable a transition to climate-friendly cooling that is also more energy efficient. By phasing down the use of climate-polluting HFCs, the Kigali Amendment is putting us on a path to avoid as much as 0.5° C by 2100, in addition to the 2.5° C listed above. The work includes significantly more benefits from improvements in energy efficiency and lifecycle refrigerant management.").

[239] United Nations (2024) *Secretary-General's Call to Action on Extreme Heat*, 17 ("Increase equitable access to and scale up lowcarbon cooling: Invest in the triple strategy of passive cooling (nature, climate sensitive urban design, reflective surfaces and smart buildings), improved energy efficiency of buildings and cooling equipment and phase-out of climatewarming gases used in cooling equipment – in line with the Global Cooling Pledge at COP 28.[72]").

[240] United Nations (2024) *Secretary-General's Call to Action on Extreme Heat*, 19 ("Take urgent measures to cut super pollutants or short-lived climate pollutants, emanating especially from the cooling sector. Prevent dumping of new inefficient equipment that uses obsolete refrigerants.").

[241] COP28UAE, United Nations Environmental Programme & Cool Coalition (2023) *Global Cooling Pledge for COP28*, 2 ("[We] Commit to ratify the Kigali Amendment by 2024 for those countries that have not already done so; Commit to support robust action through the Montreal Protocol Multilateral Fund for early action to reduce HFC consumption and to promote improved energy efficiency for the hydrochlorofluorocarbons (HCFC) phase-out and HFC phase-down; … Commit to establish national model building energy codes that incorporate market appropriate measures such as passive cooling and energy efficiency strategies at the latest by 2030 for new and refurbished buildings as appropriate for those countries with jurisdiction of national building codes, or for those countries that do not have such jurisdiction, support adoption of building energy codes at the sub-national level; … Commit to establish Minimum Energy Performance Standards (MEPS) by at the latest 2030 and aim to routinely raise ambition and progress consistent with respective national laws with a view to achieve net-zero emissions by 2050 and noting best available technology and available model regulation guidelines; … Commit to establish or update public procurement policies and guidance for low-GWP and high efficiency cooling technologies and innovative solutions where feasible or ensure broader arrangements are in place that drive such approaches in public procurement at the latest by 2030;

… Commit to pursue the life cycle management of fluorocarbons in particular addressing HFCs banks, if feasible, such as through the Initiative on Fluorocarbons Life Cycle Management[.]”). *See generally* Dickie G. (5 December 2023) *COP28 pledge to curb cooling emissions backed by 63 countries*, REUTERS.

[242] 168 CONG. REC. D1,006 (daily ed. Sept. 21, 2022) (“By 69 yeas to 27 nays (Vote No. EX. 343), two-thirds of the Senators present having voted in the affirmative, Senate agreed to the resolution of Advise and Consent to Ratification, as amended, to Treaty Document 117–1, the amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer (the ‘‘Montreal Protocol’’), adopted at Kigali on October 15, 2016, by the Twenty-Eighth Meeting of the Parties to the Montreal Protocol (the ‘‘Kigali Amendment’’), with 1 declaration…”). *See also* White House (21 September 2022) *Statement by President Joe Biden on Senate Ratification of the Kigali Amendment to the Montreal Protocol*; *and* White House (16 November 2021) *A Message to the Senate on the Amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer,* Briefing Room (“TO THE SENATE OF THE UNITED STATES: With a view to receiving the advice and consent of the Senate to ratification, I transmit herewith the Amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer (the “Montreal Protocol”), adopted at Kigali on October 15, 2016, by the Twenty-Eighth Meeting of the Parties to the Montreal Protocol (the “Kigali Amendment”). The report of the Department of State is also enclosed for the information of the Senate. The principal features of the Kigali Amendment provide for a gradual phasedown in the production and consumption of hydrofluorocarbons (HFCs), which are alternatives to ozone-depleting substances being phased out under the Montreal Protocol, as well as related provisions concerning reporting, licensing, control of trade with non-Parties, and control of certain byproduct emissions.”), *discussed in* Mason J. (16 November 2021) *White House sends Kigali amendment on climate-warming gases to Senate*, REUTERS.

[243] American Innovation and Manufacturing Act, Pub. L. No. 116-260, § 103 (2020) (codified at 42 U.S.C. § 7675). *See also* United States Environmental Protection Agency (*last updated* 25 July 2022) *Proposed Rule - Phasedown of Hydrofluorocarbons: Establishing the Allowance Allocation and Trading Program under the AIM Act*.

[244] *See* *HFCBans.com* (*last visited* 9 October 2024) (States with finalized HFC prohibitions include: California, Colorado, Delaware, Maine, Maryland, Massachusetts, New Jersey, New York, Rhode Island, Washington, Vermont, and Virginia. States with proposed bans include: Connecticut, Hawaii, New Mexico, Oregon, Pennsylvania, and Texas.).

[245] Zhao A., O’Keefe K. T. V., Binsted M., McJeon H., Bryant A., Squire C., Zhang M., Smith S. J., Cui R., Ou Y., Iyer G., Kennedy S., & Hultman N. (2024) *High-ambition climate action in all sectors can achieve a 65% greenhouse gas emissions reduction in the United States by 2035*, NPJ CLIM. ACTION 3(1): Supplementary Information, 18 (“[Current Policies:] National HFC phasedown is implemented consistent with the American Innovation and Manufacturing (AIM) Act, reducing emissions up to 47% below 2020 levels by 2035 (consistent with analysis and modeling results developed by California Air and Resources Board (CARB)).[1] [Enhanced Policies:] National HFC phasedown is implemented consistent with the AIM Act. Tier 1 states achieves additional reductions through more comprehensive measures including Significant New Alternatives Policy (SNAP) and Refrigerant Management Programs (RMP) programs, reducing emissions up to 54% below 2020 levels by 2035 (consistent with analysis and modeling results developed by CARB).[12]”). Note that this modeling study assumes maximum compliance with end-of-life disposal policies, but actual emissions of HFCs show room for increased ambition on venting and recovery; *see* United States Environmental Protection Agency (2024) INVENTORY OF U.S. GREENHOUSE GAS EMISSIONS AND SINKS: 1990-2022, 4-168 (“The additional data from the atmospheric measurements suggests additional items to investigate. The faster uptick in HFC-32 and HFC-125 emissions suggests additional emissions of R-410A compared to the model’s estimation. Further investigation into the average emission rate, the variability over time of the emission rate, stocks, lifetimes, and other factors will be investigated for the next (i.e., 2025) Inventory submission.”); Annex 3.9 (*see* Table A-113).

[246] Comparing global warming potentials over 100 years (GWP_{100}); *see* Forster P., *et. al.* (2021) *Chapter 7: The Earth’s Energy Budget, Climate Feedbacks, and Climate Sensitivity*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS (*see* Table 7.15 on the emission metrics for a select species of gases, including methane and nitrous oxide (N_2O).).

[247] Compare the global mean effective radiative forcing values under AR6 for CO_2 and N_2O: Forster P., *et. al.* (2021) *Chapter 7: The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, Table 7.8. For updated radiative forcing values based on additional years of data, *see* Forster P. M., *et al.* (2024) *Indicators of Global Climate Change 2023: annual update of key indicators of the state of the climate system and human influence*, EARTH SYST. SCI. DATA 16(6): 2625–2658, Table 3.

[248] Portmann R. W., Daniel J. S., & Ravishankara A. R. (2012) *Stratospheric Ozone Depletion Due to Nitrous Oxide: Influences of Other Gases*, PHILOS. TRANS. R SOC. LOND. B BIOL. SCI. 367(1593): 1256–1264, 1262 ("By 2008, anthropogenic N_2O was the most significant ozone-destroying compound being emitted. Owing to the phase-out of anthropogenic halocarbon emissions, it is likely to become even more dominant in the near future."). *See also* Porter I. (2019) *Mitigation of Nitrous Oxide Emissions*, Presentation at 31st Meeting of the Parties to the Montreal Protocol ("By 2050, lack of controls on N_2O will undo 25% of the benefit gained by the Montreal Protocol to reducing ODS from the ozone layer.").

[249] World Meteorological Organization, United Nations Environment Programme, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, & European Commission (2022) SCIENTIFIC ASSESSMENT OF OZONE DEPLETION: 2022, Global Ozone Research and Monitoring Project– GAW Report No. 278, World Meteorological Organization, 99 ("Several recent publications have found that global N_2O emission increases have been accelerating over the last two decades and by now exceed some of the highest projections (Thompson et al., 2019; Tian et al., 2020; IPCC, 2021).").

[250] National Oceanic and Atmospheric Administration (5 April 2024) *No sign of greenhouse gases increases slowing in 2023* ("Increases in atmospheric nitrous oxide during recent decades are mainly from use of nitrogen fertilizer and manure from the expansion and intensification of agriculture. Nitrous oxide concentrations are 25% higher than the pre-industrial level of 270 ppb."). As of 2024, the current atmospheric concentration of N_2O was over 337 ppb; 2024 continued this trend of growing N_2O in the atmosphere; *see also* United States Department of Commerce, *Global Monitoring Laboratory - Carbon Cycle Greenhouse Gases* (*last visited* 22 April 2025).

[251] Tian H., *et al.* (2024) *Global Nitrous Oxide Budget (1980–2020)*, EARTH SYS. SCI. DATA 16: 2543–2604, 2548–2549 ("[T]he mean annual growth rate increased from 0.76 (0.55–0.95) ppb yr^{-1} in the 2000s to 0.96 (0.79– 1.15) ppb yr^{-1} in the 2010s, with significant seasonal and interannual variation. In 2020, the N_2O atmospheric growth rate was 1.33 ppb yr^{-1} (1.38 ppb yr^{-1} in 2021), higher than any previous observed year, and more than 30 % higher than the average value in the 2010s. Due to the rapid increase in global N_2O emissions, observed atmospheric N_2O mole fractions in recent years have begun to exceed the predicted levels under all scenarios in the Coupled Model Intercomparison Project Phase 6 (CMIP6) for the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2021; Gidden et al., 2019; Tian et al., 2020). N_2O emissions are expected to continue increasing in the coming decades due to the growing demand for food, feed, fiber, and energy as well as a rising source from waste generation and industrial processes (Davidson and Kanter, 2014; Reay et al., 2012).").

[252] World Meteorological Organization, United Nations Environment Programme, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, & European Commission (2022) SCIENTIFIC ASSESSMENT OF OZONE DEPLETION: 2022, Global Ozone Research and Monitoring Project– GAW Report No. 278, World Meteorological Organization, 99 ("Anthropogenic emissions N_2O were driving that increase, and these alone (43%, Tian et al., 2020) were equal to more than two times the ODP-weighted emissions from all CFCs in 2020. For context, when compared to the CFC emission peak from 1987, those 2020 anthropogenic N_2O emissions were equal to more than 20 % the ODP-weighted emissions from CFCs in that year.").

[253] Tian H., *et al.* (2024) *Global Nitrous Oxide Budget (1980–2020)*, EARTH SYS. SCI. DATA 16: 2543–2604, 2545 ("According to BU estimates, the increase in global N_2O emissions was primarily due to a 40% increase in anthropogenic emissions from 4.8 (3.1–7.3) Tg yr^{-1} in 1980 to 6.7 (3.3–10.9)Tg yr^{-1} in 2020.").

[254] National Oceanic and Atmospheric Administration (5 April 2024) *No sign of greenhouse gases increases slowing in 2023* ("Levels of the three most important human-caused greenhouse gases – carbon dioxide (CO_2), methane and nitrous oxide – continued their steady climb during 2023, according to NOAA scientists. While the rise in the three heat-trapping gases recorded in the air samples collected by NOAA's Global Monitoring Laboratory (GML) in 2023 was not quite as high as the record jumps observed in recent years, they were in line with the steep increases observed during the past decade."). 2024 continued this trend of growing N_2O in the atmosphere; *see* United States Department of Commerce, *Global Monitoring Laboratory - Carbon Cycle Greenhouse Gases* (*last visited* 22 April 2025).

[255] United Nations Environment Programme & Food and Agriculture Organization of the United Nations (2024) GLOBAL NITROUS OXIDE ASSESSMENT, 20–21 ("Anthropogenic nitrous oxide emissions have grown steadily since the pre-industrial era and have accelerated since the Green Revolution. Between 1980 and 2022, atmospheric concentrations increased from 301 to 336 parts per billion. Agriculture is currently the source of 75 per cent of those emissions, of which approximately 90 per cent comes from the use of synthetic fertilisers and manure on agricultural soils and 10 per cent from manure management. … Industrial sources account for approximately 5 per cent of current anthropogenic nitrous oxide emissions. The dominant sources are the production of adipic acid, primarily used in synthetic fibres and foam, and nitric acid, mainly used in the manufacture of fertilisers, munitions and adipic acid. … The remaining 20 per cent of anthropogenic nitrous oxide emissions come from fossil fuel combustion, wastewater treatment, aquaculture, biomass burning, and other sources."). *See also* Tian H., *et al.* (2024) *Global Nitrous Oxide Budget (1980–2020)*, EARTH SYS. SCI. DATA 16: 2543–2604, 2564–2565, 2564–2565, 2575 (*see* Table 3 on the global N_2O budget (in $TgNyr^{-1}$) for the 1980s, the 1990s, the 2000s, the 2010s, and the year 2020; "In this study, N_2O fluxes are expressed in teragrams of N_2O-N per year, where 1 TgN_2O Nyr^{-1} (1 $TgNyr^{-1}$)=10^{12} gN_2O-N yr^{-1}=1.57 x 10^{12} g N_2Oyr^{-1}, with change rates in N_2O fluxes expressed in teragrams of nitrous oxide-nitrogen per year squared ($TgNyr^{-2}$), representing the first derivative of annual N_2O fluxes calculated by the linear regression method."; "Indirect agricultural emissions include emissions from anthropogenic nitrogen additions to inland waters, estuaries, and coastal vegetation as well as N deposition on land.").

[256] Grubb M., *et. al.* (2022) *Chapter 1: Introduction and Framing*, *in* CLIMATE CHANGE 2022: MITIGATION OF CLIMATE CHANGE, Idris I. E. & Lowe J. (eds.), 166 ("FOOTNOTE 5: AFOLU accounted for about 13% of CO_2, 44% of CH_4 and 82% of N_2O global anthropogenic GHG emissions in 2007-2016 (SRCCL SPM A3).").

[257] Nabuurs, G. *et. al.* (2022) *Chapter 7: Agriculture, Forestry, and Other Land Uses (AFOLU)*, *in* CLIMATE CHANGE 2022: MITIGATION OF CLIMATE CHANGE, Angers, D. & Ravindranath, N.H. (eds.), 750 ("Agricultural CH_4 and N_2O emissions are estimated to average 157 ± 47.1 $MtCH_4$ yr^{-1} and 6.6 ± 4.0 MtN_2O yr^{-1} or 4.2 ± 1.3 and 1.8 ± 1.1 $GtCO_2$-eq yr^{-1} (using IPCC AR6 GWP100 values for CH_4 and N_2O) respectively between 2010 and 2019.").

[258] Tian H., *et al.* (2024) *Global Nitrous Oxide Budget (1980–2020)*, EARTH SYS. SCI. DATA 16: 2543–2604, 2564–2565, 2575 ("In this study, N_2O fluxes are expressed in teragrams of N_2O-N per year, where 1 TgN_2O Nyr^{-1} (1 $TgNyr^{-1}$)=10^{12} gN_2O-N yr^{-1}=1.57 x 10^{12} g N_2Oyr^{-1}, with change rates in N_2O fluxes expressed in teragrams of nitrous oxide-nitrogen per year squared ($TgNyr^{-2}$), representing the first derivative of annual N_2O fluxes calculated by the linear regression method."; "Indirect agricultural emissions include emissions from anthropogenic nitrogen additions to inland waters, estuaries, and coastal vegetation as well as N deposition on land."; *see* Table 3 on the global N_2O budget (in $TgNyr^{-1}$) for the 1980s, the 1990s, the 2000s, the 2010s, and the year 2020).

[259] Tian H., *et al.* (2024) *Global Nitrous Oxide Budget (1980–2020)*, EARTH SYS. SCI. DATA 16: 2543–2604, 2571 ("The total anthropogenic N_2O emissions from China increased at an average rate of 18.9 × 10^{-3} Tg N yr^{-2} during 1980–2020, which was the largest among the 18 regions and contributed 40 % of the increase in global anthropogenic N2O emissions. … Nitrogen additions in agriculture were the dominant source of N_2O emissions, contributing 48 % of the total emissions (0.68, 0.48–1.03 Tg N yr^{-1}).").

[260] International Energy Agency (2023) CREDIBLE PATHWAYS TO 1.5 °C - FOUR PILLARS FOR ACTION IN THE 2020S, 12 ("Tackling emissions of nitrous oxide (N_2O) is also important to achieve climate goals. The agricultural sector is responsible for about four-fifths of anthropogenic N_2O emissions. In the STEPS [Stated Policies Scenario], agricultural N_2O emissions rise by around 8% to 2030 compared to 2021 levels, whereas in the NZE Scenario they

fall by around 2% over this period, mainly due to efficiency gains in crop management and fertilizer use. The majority of energy-related N_2O emissions today are associated with the industry sector and road transport. In the NZE Scenario, energy-related N_2O emissions fall by around 30% between 2021 - 2030, almost entirely associated with reductions in coal and oil use.").

[261] Climate & Clean Air Coalition (12 November 2024) *The Sprint to Cut Climate Super Pollutants: COP29 Summit on Methane and Non-CO2 GHGs Fact Sheet* ("The United Nations Environment Program (UNEP) and Food and Agriculture Organization (FAO) launched the first ever Global N2O Assessment, followed by a commitment by the UNEP-convened Climate and Clean Air Coalition to advance scientific understanding in 2025 of opportunities to reduce the climate impacts of tropospheric ozone—an air pollutant and greenhouse gas that is formed in the atmosphere from interactions of other gases, and which is the third-largest contributor to climate change after CO2 and methane.").

[262] United Nations Environment Programme & Food and Agriculture Organization of the United Nations (2024) GLOBAL NITROUS OXIDE ASSESSMENT, 67 ("Under the reference scenario, which assumes a continuation of current trends in nitrogen production, consumption and loss, nitrous oxide emissions increase by approximately 30 per cent by 2050 and 110 per cent by 2100, relative to 2020. Under the technical reductions scenario, based on the implementation of all currently available technologies and practices, emissions decrease by approximately 20 per cent by 2050 and 15 per cent by 2100, relative to 2020. Under the technical reductions and societal change scenario, which considers additional transformative changes including dietary shifts towards the lower consumption of animal protein, emissions decrease by approximately 40 per cent by 2050 and 60 per cent in 2100, relative to 2020.").

[263] United Nations Environment Programme & Food and Agriculture Organization of the United Nations (2024) GLOBAL NITROUS OXIDE ASSESSMENT, 16 ("If nitrous oxide emissions continue to increase at their current rate, there is no plausible pathway to limiting global warming to 1.5° Celsius in the context of sustainable development, as defined in the Paris Agreement. … Even keeping current nitrous oxide emissions constant would constrain society's capacity to limit global warming to 1.5° Celsius and require much greater and costlier reductions of carbon dioxide and methane emissions."). *See also* Tian H., *et al.* (2024) *Global Nitrous Oxide Budget (1980–2020)*, EARTH SYS. SCI. DATA 16: 2543–2604, 2549 ("Significant reductions in N_2O emissions are required along with net CO_2 emissions to stabilize the global climate system. For pathways consistent with the remaining carbon budget of 1.5, 1.7, and 2 °C stabilization, and assuming that all greenhouse gases (GHGs) should be cut in equal proportion to their contribution to anthropogenic radiative forcing, global N_2O emissions need to be reduced by 22 %, 18 %, and 11 %, respectively, by 2050 (Rogelj and Lamboll, 2024). In addition, N_2O mitigation could reduce ozone loss comparable to the depletion potential of the global chlorofluorocarbons (CFCs) stock in old air conditioners, refrigerators, insulation foams, and other units (UNEP, 2013). All in all, implementing N_2O mitigation will contribute to achieving a set of United Nations Sustainable Development Goals (United Nations, 2016)."). Previous work demonstrated mitigation potentials of 1.67 $GtCO_2e$ (on a GWP_{100} basis) by 2050 with 0.94 $GtCO_2e$ from agriculture and about 0.6 $GtCO_2e$ from industry in 2050; *see* Harmsen J. H. M., van Vuuren D. P., Nayak D. R., Hof A. F., Höglund-Isaksson L., Lucas P. L., Nielsen J. B., Smith P., & Stehfest E. (2019) *Long-term marginal abatement cost curves of non-*CO_2 *greenhouse gases*, ENVIRON. SCI. POLICY 99: 136–149, 145 (Table 2).

[264] United Nations Environment Programme & Food and Agriculture Organization of the United Nations (2024) GLOBAL NITROUS OXIDE ASSESSMENT, 67 ("Under the technical reductions and societal change scenario, which considers additional transformative changes including dietary shifts towards the lower consumption of animal protein, emissions decrease by approximately 40 per cent by 2050 and 60 per cent in 2100, relative to 2020.").

[265] United Nations Environment Programme & Food and Agriculture Organization of the United Nations (2024) GLOBAL NITROUS OXIDE ASSESSMENT, 16 ("Ambitious nitrous oxide abatement could avoid the equivalent of up to 235 billion tonnes of carbon dioxide emissions by 2100, which is approximately 6 years of current carbon dioxide emissions from fossil fuel burning."), *discussed in* Volcovici V. (31 October 2024) *World will miss Paris climate target as nitrous oxide rises, report says*, REUTERS ("Taking global action to reduce emissions of nitrous oxide (N_2O) could avoid the equivalent of up to 235 billion metric tons of carbon dioxide emissions by 2100, [the Global Nitrous Oxide Assessment] said.").

[266] United Nations Environment Programme & Food and Agriculture Organization of the United Nations (2024) GLOBAL NITROUS OXIDE ASSESSMENT, 71 ("For the reference scenario, which assumes a continuation of current nitrogen production, consumption and loss trends, the RCP/SSP combination is RCP 4.5/SSP 2 from 2020 to 2050 coupled with low nitrogen-policy ambition, and RCP 7.0-SSP 3 from 2050 to 2100."); 99 ("Including the effects of the methane emissions reductions associated with the decrease in livestock numbers that is required to meet the sustainable nitrogen management goals, both scenarios [technical measures and technical measures + societal transformation] would lead to about 0.06-0.07ºC of warming by 2050 with a cooling approaching 0.1ºC by 2100 under the technical reductions and societal change scenario (Figure 4.3)."); 95 (*see* Table 4.1 for estimated radiative forcing from 2040–2050 for these scenarios, which shows the combined effects of ozone, aerosols, nitrous oxide, and methane responses). Previous work estimated a similar small reduction in nitrous oxide but did not consider effects of these other co-occurrent emissions; *see* World Meteorological Organization, United Nations Environment Programme, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, & European Commission (2022). SCIENTIFIC ASSESSMENT OF OZONE DEPLETION: 2022, Global Ozone Research and Monitoring Project– GAW Report No. 278, World Meteorological Organization, 393 ("A reduction in future N_2O emissions from that in the baseline scenario (SSP2-4.5) to that in the SSP scenario with the strongest N_2O mitigation (SSP1-1.9) results in a 0.5 DU increase in ozone averaged over 2020 to 2070, or about one-quarter of the impact of eliminating all emissions from controlled ODSs beginning in 2023. This emission reduction also leads to a radiative forcing reduction of 43 mW m^{-2} averaged over 2023–2100. The magnitude of this N_2O reduction represents a decrease in anthropogenic N_2O emissions of 3% compared with the baseline scenario when averaged over 2020 –2070."; *see* Figure 7-1 showing that N_2O emissions reduction to SSP1-1.9 results in a decrease in radiative forcing of about 0.04 W m^{-2} while eliminating all high-GWP HFC emissions results in a decrease in radiative forcing of about 0.07 Wm^{-2}).

[267] United Nations Environment Programme & Food and Agriculture Organization of the United Nations (2024) GLOBAL NITROUS OXIDE ASSESSMENT, 17 ("Through 2050, ambitious nitrous oxide abatement could provide roughly the same ozone benefits as the 2007 Montreal Protocol agreement to accelerate the phase-out of hydrochlorofluorocarbons. Through 2100, the benefits could accumulate to more than five times those of the accelerated phase out.").

[268] United Nations Environment Programme & Food and Agriculture Organization of the United Nations (2024) GLOBAL NITROUS OXIDE ASSESSMENT, 17 ("The lowest levels of ozone this century and beyond are expected to occur if nitrous oxide emissions continue unabated and carbon dioxide and methane are abated consistent with climate goals. In such a future, by the end of the century much of the world's population could be exposed to ultraviolet levels larger than peak ozone depletion in 1995-2005."). *See also* World Meteorological Organization, United Nations Environment Programme, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, & European Commission (2022). SCIENTIFIC ASSESSMENT OF OZONE DEPLETION: 2022, Global Ozone Research and Monitoring Project– GAW Report No. 278, World Meteorological Organization, 258 ("Therefore, in general, the ozone return date is expected to be later if there are increases in N_2O or earlier if there are decreases in N_2O. However, the effect of future increases in N_2O varies with altitude and also depends on the temporal evolution of other GHGs."); Butler A. H., Daniel J. S., Portmann R. W., Ravishankara A. R., Young P. J., Fahey D. W., & Rosenlof K. H. (2016) *Diverse policy implications for future ozone and surface UV in a changing climate*, ENV. RES. LETT. 11(6): 064017, 1–7, 4 ("A key point is that if the world were to achieve reductions of CO_2 and CH_4 concentrations to RCP 2.6 levels, N_2O mitigation would become important to avoid exacerbation of both climate change and ozone layer depletion.").

[269] United Nations Environment Programme & Food and Agriculture Organization of the United Nations (2024) GLOBAL NITROUS OXIDE ASSESSMENT, 134 ("Nitrous oxide emissions from adipic acid and nitric acid production industries could be nearly eliminated by adoption of existing and relatively low-cost abatement measures (USD 1,600–6,000 per tonne of nitrous oxide; USD 6–22 per tonne of carbon dioxide equivalent). It is low-hanging fruit for near-term abatement and even though it currently represents approximately 5 per cent of anthropogenic emissions, this could increase in the future."). *See also* Garthwaite J. (7 October 2020) *Stanford expert explains why laughing gas is a growing climate problem*, STANFORD REPORT ("Fossil fuel use and industry contribute about one-seventh of emissions from human activities. China has particularly high industrial emissions. The largest point source here in the U.S. is a chemical plant in Florida that makes adipic acid for nylon production. Its N_2O emissions in 2018 were

equivalent to the carbon dioxide pollution from two million cars. The company is working to reduce it. Reducing emissions from industrial sources is the lowest-hanging fruit in our arsenal of N_2O mitigation.").

[270] In contrast to fossil fuel combustion and agricultural sources of N_2O, industrial production of nitric and adipic acid does not co-emit cooling aerosols, so mitigating industrial emissions does not unmask additional warming; *see* United Nations Environment Programme & Food and Agriculture Organization of the United Nations (2024) GLOBAL NITROUS OXIDE ASSESSMENT, 92–93 ("Industrial and waste sector nitrous oxide emissions are not associated with substantial amounts of ammonia but there are small co-emissions of nitrogen oxides. Analysis of the effects of policies to reduce nitrous oxide emissions therefore requires assessment of the impacts of both the nitrous oxide changes and the changes in climate drivers resulting from the co-emitted species. Nitrogen oxides emissions lead to multiple changes in climate drivers in the troposphere, including increased tropospheric ozone, which causes warming; reductions in methane, due to increased formation of the oxidising hydroxyl radical, that causes cooling; and increases in both nitrate and secondary organic aerosols, which cause cooling. Ammonia emissions lead to increases in aerosols as well, causing cooling. Hence, while the direct impact of nitrous oxide reductions would be cooling, given that nitrous oxide is a powerful greenhouse gas, decreases in co-emissions primarily cause warming, often described as unmasking of greenhouse gas-induced warming due to reductions in cooling aerosols. In response to changes in emissions, the aerosols, ozone and methane responses would be rapid whereas changes in nitrous oxide would take place slowly over a century."); *and* Gong C., *et al.* (2024) *Global net climate effects of anthropogenic reactive nitrogen*, NATURE 632(8025): 557–563, 561 ("NO_x emissions emitted from fossil fuel combustion dominated the net cooling effects of non-agricultural sources. Higher atmospheric NO_x burden not only induced a higher nitrate aerosol burden but also significantly decreased the atmospheric mole fraction of CH_4 through increasing atmospheric OH.").

[271] United States Environmental Protection Agency (2012) GLOBAL ANTHROPOGENIC NON-CO_2 GREENHOUSE GAS EMISSIONS: 1990–2030, 41 ("Between 1990 and 2005, N_2O emissions from production of nitric and adipic acid has decreased 37 percent, from 200 $MtCO_2e$ to 126 $MtCO_2e$ (see Table 4-2). Over this time period, production of nitric and adipic acid has increased. The decline in historical emissions is mostly due to widespread installation of abatement technologies in the adipic acid industry (Reimer et al, 1999). Most production capacity in these industries has been located in the OECD, but the proportion of emissions in the OECD has declined. In 1990, the OECD accounted for 83 percent of global N_2Oemissions from this source, whereas the OECD is estimated to account for 68 percent of global emissions in 2005.").

[272] United States Environmental Protection Agency (2019) GLOBAL NON-CO_2 GREENHOUSE GAS EMISSION PROJECTIONS & MITIGATION: 2015–2050, 28 ("The global abatement potential is 231 $MtCO_2e$, or 86% of projected emissions in 2030.").

[273] Davidson E. A. & Winiwarter W. (2023) *Urgent abatement of industrial sources of nitrous oxide*, NAT. CLIM. CHANGE 13: 599–601, 600 ("Of the 21 adipic acid plants worldwide, 11 are in China, making it the largest emitter of N_2O (Table 2)."); Hasanbeigi A. & Sibal A. (2023) STOPPING A SUPER-POLLUTANT: N_2O EMISSIONS ABATEMENT FROM GLOBAL ADIPIC ACID PRODUCTION, Global Efficiency Intelligence, 2 ("There are estimated to be 39 operational facilities globally producing adipic acid while almost two thirds of the global adipic acid production takes place in China and U.S. Adipic acid production is one of the largest sources of nitrous oxide (N_2O) emissions.").

[274] Davidson E. A. & Winiwarter W. (2023) *Urgent abatement of industrial sources of nitrous oxide*, NAT. CLIM. CHANGE 13: 599–601, 600 ("Of the 21 adipic acid plants worldwide, 11 are in China, making it the largest emitter of N_2O (Table 2).").

[275] Davidson E. A. & Winiwarter W. (2023) *Urgent abatement of industrial sources of nitrous oxide*, NAT. CLIM. CHANGE 13: 599–601, 600 ("Of the two plants in the United States, one reduces over 95% of its emissions, and the other has a variable abatement history, with large increases in emissions since 2010.").

[276] Hasanbeigi A. & Sibal A. (2023) STOPPING A SUPER-POLLUTANT: N_2O EMISSIONS ABATEMENT FROM GLOBAL ADIPIC ACID PRODUCTION, Global Efficiency Intelligence, 2, 9 ("There are estimated to be 39 operational facilities globally producing adipic acid while almost two thirds of the global adipic acid production takes place in China and

U.S. Adipic acid production is one of the largest sources of nitrous oxide (N_2O) emissions. … Global facilities are currently abating N_2O emissions at different rates. Our key assumptions for the current abatement rates are as follow: U.S. adipic acid production: There are two adipic acid producers in the U.S. One reported to abate N_2O emissions at 97-99% rate in the last 5 years. We assumed a 98% abatement rate for this facility. The other plant's baseline abatement rate was assumed at 80%, which reflects a 5-year average (ClimeCo Corporation, 2019). Chinese adipic acid production: There are 11 producers of adipic acid in China. Several reports, in addition to expert testimony, led to the conclusion that Chinese adipic acid producers are not utilizing N_2O abatement technology (U.S. EPA, 2019, McKenna et al., 2020, Qing et al., 2020). Other countries' adipic acid production: For all others producers including Brazil, Japan, South Korea, France, Germany, and Italy we assumed abatement of 98% of N_2O emissions."); *as reported in* McKenna, P. (1 May 2023) *Eleven Chemical Plants in China and One in the U.S. Emit a Climate Super-Pollutant Called Nitrous Oxide That's 273 Times More Potent Than Carbon Dioxide*, INSIDE CLIMATE NEWS ("Neither the U.S. nor China require adipic acid manufacturers to reduce their nitrous oxide emissions."). *See also* McKenna, P., Pike, L., Northrop, K. (6 August 2020) *'Super-pollutant' emitted by 11 Chinese chemical plants could equal a climate catastrophe*, INSIDE CLIMATE NEWS ("Eleven adipic acid plants in China produce nearly half of the world's adipic acid… an Inside Climate News investigation, based on dozens of interviews and a review of hundreds of pages of documents from the Chinese government, the United Nations, and Chinese state media, strongly suggests that when funding for the U.N. program ended, so too did nearly all of the emissions reductions. This likely occurred despite the availability of proven, low-cost abatement technology. If the vast majority of the plants' emissions are released, unabated into the atmosphere, their collective emissions would exceed the yearly greenhouse gas emissions from all passenger vehicles in California, the most populous state in America, as well as the emissions from all cars in Beijing and Shanghai, China's two largest megacities.").

[277] McKenna P. (23 July 2024) *Biden Administration Targets Domestic Emissions of Climate Super-Pollutant With Eye Toward U.S.-China Climate Agreement*, INSIDE CLIMATE NEWS ("The United States and China account for nearly 80 percent of industrial N_2O emissions.").

[278] United States Environmental Protection Agency (2019) GLOBAL NON-CO_2 GREENHOUSE GAS EMISSION PROJECTIONS & MITIGATION: 2015–2050, 26 (*see* "Projected Emissions & Top Emitting Countries." Total emissions of industrial N_2O in 2030 are 270 $MtCO_2e$. China contributes 175 $MtCO_2e$ to this, while the United States contributes 29 $MtCO_2e$.").

[279] United States Department of State (14 November 2023) *Sunnylands Statement on Enhancing Cooperation to Address the Climate Crisis*, Press Release ("The two countries intend to cooperate on respective measures to manage nitrous oxide emissions.").

[280] United States Department of State (10 May 2024) *Readout on Meeting of the U.S.-China Working Group on Enhancing Climate Action in the 2020s*, Press Release ("On May 8-9, the United States hosted in Washington, D.C., a meeting of the U.S.-China Working Group on Enhancing Climate Action in the 2020s, which is co-led by Senior Advisor to the President for International Climate Policy John Podesta and PRC Special Envoy for Climate Change Liu Zhenmin and includes relevant officials from the two countries. … They will also engage in technical cooperation and capacity-building for measurement and abatement solutions of other non-CO2 greenhouse gases, including industrial N2O as well as tropospheric ozone precursors.").

[281] McKenna P. (23 July 2024) *Biden Administration Targets Domestic Emissions of Climate Super-Pollutant With Eye Toward U.S.-China Climate Agreement*, INSIDE CLIMATE NEWS (""We are dealing with our emissions quickly in the United States, of industrial N2O, and rolling up sleeves to tackle a far bigger prize that's also very tractable in China," a senior Biden administration official who spoke on condition of anonymity said on a call with reporters in advance of the event. … At the White House summit Tuesday on climate super-pollutants, and the separate nonprofit-organized event focused exclusively on nitrous oxide, U.S. policymakers, researchers, industry leaders and environmental organizations outlined a plan to significantly reduce industrial emissions in the next decade. The events focused on U.S. reductions that could help drive a bilateral U.S.-China effort. Hu Jianxin, a professor from Peking University, also participated remotely from China via a video call. U.S. companies showcased new actions that, by

early 2025, will reduce overall U.S. industrial emissions of nitrous oxide by over 50 percent since 2020, according to a White House fact sheet.”).

[282] United Nations Environment Programme & Food and Agriculture Organization of the United Nations (2024) GLOBAL NITROUS OXIDE ASSESSMENT, 174 (“Ambitious nitrous oxide abatement is possible without threatening food security. Certain management practices and technologies can even make food production more resilient to current and future environmental challenges by, for example, prolonging the time that plant-available nitrogen is present in the soil (Chapter 5).”).

[283] United Nations Environment Programme & Food and Agriculture Organization of the United Nations (2024) GLOBAL NITROUS OXIDE ASSESSMENT, 174–175 (“Other action, however, requires more fundamental, systemic change, as outlined in Chapter 5. This is largely the case in agriculture and the broader agri-food system, ranging from the re-integration of crop and livestock production, the development and adoption of genetically-engineered plants and microbial solutions to transform non-leguminous crops into nitrogen fixers, and changes in consumer diets to significantly lower animal protein consumption. These kinds of systemic changes are likely to be necessary to go beyond 50 per cent abatement of nitrous oxide emissions from the agricultural sector and the global food system relative to 2020, as noted in Chapters 3 and 5.”).

[284] United Nations Environment Programme & Food and Agriculture Organization of the United Nations (2024) GLOBAL NITROUS OXIDE ASSESSMENT, 141, 153 (“[C]urrent efforts to abate nitrous oxide emissions from croplands and grasslands focus primarily on improving NUE of synthetic nitrogen fertilisers and manures applied to soils (Table 3.4), so that more of the applied nitrogen is taken up by crops and less is lost to the air and water. These measures may include enhanced efficiency fertilisers (EEF) such as nitrification and urease inhibitors and slow-release fertilisers, amendments such as biochar and microbial inoculants, crop and cultivar choices, conservation tillage, and irrigation management. Ideally, these measures become part of a holistic nutrient management approach, such as the 4R concept of nutrient stewardship the application of nutrients at the right rate, right type, right time, and right placement. The effectiveness of each measure is likely to be regionally or locally specific and may also have co-benefits for nutrient, water and energy management.”; “Strategies to reduce emissions from manure management include improving the balance of nutrient inputs in animal feed, reducing grazing intensity, anaerobic digestion of mature, decreased manure storage time, sealed manure storage with flaring, timing of manure application to soils, application of nitrification inhibitors to manure or following urine deposition to soils, application of urease inhibitors with or before urine deposition onto soils, and management of soil water content and drainage (Montes *et al.* 2013).”).

[285] Balafoutis A., Beck B., Fountas S., Vangeyte J., van der Wal T., Soto I., Gómez-Barbero M., Barnes A., & Eory V. (2017) *Precision Agriculture Technologies Positively Contributing to GHG Emissions Mitigation, Farm Productivity and Economics*, SUSTAINABILITY 9(8): 1339, 1–28, 9 (“Tekin (2010) estimated that VRNA can increase wheat production between 1% and 10% offering savings in nitrogen fertilisation between 4% and 37%.”).

[286] Dreyfus G., Frederick C., Larkin E., Powers Y., & Chatterjee J. (2023) *Reducing nitrous oxide emissions from smallholder farmer agriculture through site specific nutrient management,* Precision Development & Institute for Governance & Sustainable Development, 3 (“Addressing the precision nutrient management gap for smallholder farmers in the Global South is a critical priority for achieving both anti-poverty and climate change goals, especially as the use of nitrogen fertilizer in Global South countries rises[15] in coming years to meet increasing global food demands.”). *See also* United Nations Environment Programme & Food and Agriculture Organization of the United Nations (2024) GLOBAL NITROUS OXIDE ASSESSMENT, 146 (“Adoption of technologies to improve NUE and reduce nitrous oxide emissions involves more than developing and introducing technological options. It should be noted that the cost estimates cited above refer to implementation costs and may not include the regionally-specific financial incentives needed to encourage farmer adoption. The human health, ecosystem health and climate co-benefits (Figure 5.3) could justify cost sharing of implementation costs through innovative public policies and financial incentives. Economic considerations, including those under farmers’ control and those that are imposed by policies and markets, are crucial for farmer decision making. In addition, social factors, such as farmer demographics and their perceptions of trusted sources of information are also important influences (Davidson et al. 2015). The importance of farmer

adoption of best management practices and technologies for nitrous oxide abatement and other nitrogen pollution mitigation should not be underestimated, and should be a key focus of future research efforts.”).

[287] *SOP, Save Our Planet* (*last visited* 28 August 2023).

[288] *See* Peterson C., El Mashad H. M., Zhao Y., Pan Y., & Mitloehner F. M. (2020) *Effects of SOP Lagoon Additive on Gaseous Emissions from Stored Liquid Dairy Manure*, SUSTAINABILITY 12(4): 1–17, 14–15 (“These studies seem to indicate that the applied HIGH dose of SOP Lagoon might decrease the number of methanogens that produce methane during the storage of manure as well as hydrolytic microorganisms and their excreted enzymes that biodegrade organic nitrogen into ammonium.”); *and* Maris S. C., Capra F., Ardenti F., Chiodini M. E., Boselli R., Taskin E., Puglisi E., Bertora C., Poggianella L., Amaducci S., Tabaglio V., & Fiorini A. (2021) *Reducing N Fertilization without Yield Penalties in Maize with a Commercially Available Seed Dressing*, AGRONOMY 11(3): 407, 1–19, 1 (“[W]e concluded that under our experimental conditions SCM [SOP® COCUS MAIZE+] may be used for reducing N [nitrogen] input (-30%) and N_2O emissions (-23%), while contemporarily maintaining maize yield. Hence, SCM can be considered an available tool to improve agriculture’s alignment to the United Nation Sustainable Development Goals (UN SDGs) and to comply with Europe’s Farm to Fork strategy for reducing N-fertilizer inputs.”). *See also* SOP, Save Our Planet, *Read the SOP Scientific Works* (*last visited* 28 August 2023).

[289] United Nations Environment Programme & Food and Agriculture Organization of the United Nations (2024) GLOBAL NITROUS OXIDE ASSESSMENT, 92–93 (“Anthropogenic emissions of nitrous oxide come primarily from agricultural sources, with a smaller contribution from waste and industry. There has been limited progress on mitigating anthropogenic nitrous oxide emissions even though it is the third strongest driver of global warming to date, and, as it has an atmospheric residence time of more than a century, early action is essential to avoid a long-term buildup of concentrations in the atmosphere (Forster et al. 2021). The agricultural practices that lead to nitrous oxide emissions also drive emissions of nitrogen oxides and ammonia, often referred to as co-emissions. Industrial and waste sector nitrous oxide emissions are not associated with substantial amounts of ammonia but there are small co-emissions of nitrogen oxides. Industrial and waste sector nitrous oxide emissions are not associated with substantial amounts of ammonia but there are small co-emissions of nitrogen oxides. Analysis of the effects of policies to reduce nitrous oxide emissions therefore requires assessment of the impacts of both the nitrous oxide changes and the changes in climate drivers resulting from the co-emitted species. Nitrogen oxides emissions lead to multiple changes in climate drivers in the troposphere, including increased tropospheric ozone, which causes warming; reductions in methane, due to increased formation of the oxidising hydroxyl radical, that causes cooling; and increases in both nitrate and secondary organic aerosols, which cause cooling. Ammonia emissions lead to increases in aerosols as well, causing cooling.”). *See also* United Nationals Environment Programme (16 January 2023) *Four reasons why the world needs to limit nitrogen pollution* (“Another issue is agricultural ammonia emissions. This is a gaseous form of nitrogen, which is emitted into the atmosphere from the housing, storage and spreading of animal manure and the spreading of synthetic fertilizer. While ammonia is not a greenhouse gas, when it’s released into the air, it acts as a base for emissions of nitrous oxide, a potent greenhouse gas. … Ammonia emissions, as well as contributing to climate change, are an important driver for fine particulate matter pollution, reducing air quality and increasing adverse effects on human health.”).

[290] United Nations Environment Programme & Food and Agriculture Organization of the United Nations (2024) GLOBAL NITROUS OXIDE ASSESSMENT, 88 (“The air quality improvements resulting from the improved nitrogen management scenarios lead to roughly 4 million avoided premature deaths due to decreased fine particulate matter and ozone exposure over the next decade, and approximately 20 million avoided premature deaths by 2050.”).

[291] United Nations Environment Programme & Food and Agriculture Organization of the United Nations (2024) GLOBAL NITROUS OXIDE ASSESSMENT, 91 (“Ambitious nitrous oxide abatement could avoid cataract cases increasing by 0.2-0.8 per cent and squamous cell carcinoma cases bhy 2.2.-9.8 per cent by 2080-2090, depending on latitude.”). *See also* United States Environmental Protection Agency (16 July 2024) *Health and Environmental Effects of Ozone Layer Depletion* (“Ozone layer depletion increases the amount of UVB that reaches the Earth’s surface. Laboratory and epidemiological studies demonstrate that UVB causes non-melanoma skin cancer and plays a major role in

malignant melanoma development. In addition, UVB has been linked to the development of cataracts, a clouding of the eye's lens.").

[292] Young P. J., Harper A. B., Huntingford C., Paul N. D., Morgenstern O., Newman P. A., Oman L. D., Madronich S., & Garcia R. R. (2021) *The Montreal Protocol protects the terrestrial carbon sink*, NATURE 596(7872): 384–388, 384 ("[O]zone-depleting substances are potent greenhouse gases[4–7]. The avoided ultraviolet radiation and climate change also have co-benefits for plants and their capacity to store carbon through photosynthesis[8], but this has not previously been investigated. Here, using a modelling framework that couples ozone depletion, climate change, damage to plants by ultraviolet radiation and the carbon cycle, we explore the benefits of avoided increases in ultraviolet radiation and changes in climate on the terrestrial biosphere and its capacity as a carbon sink.").

[293] United Nations Environment Programme & Food and Agriculture Organization of the United Nations (2024) GLOBAL NITROUS OXIDE ASSESSMENT, 19 ("A sustainable nitrogen management approach would deliver significant additional benefits for water quality, soil health and the structure and functioning of ecosystems. Reducing nitrogen run-off would, for example, lower the risk of eutrophying water bodies and contaminating drinking water supplies, while reducing such associated human health impacts as decreasing the risk of colon cancer."). *See also* Richardson K., *et al.* (2023) *Earth beyond six of nine planetary boundaries*, SCI. ADV. 9(37): 1–16, 8–9 ("For both N and P, the anthropogenic release of reactive forms to land and oceans is of interest, as altered nutrient flows and element ratios have profound effects on ecosystem composition and long-term Earth system effects. Some of today's changes will only be seen on evolutionary time scales, while others are already affecting climate and biosphere integrity. … The planetary boundary for N is the application rate of intentionally fixed N to the agricultural system of 62 Tg of N $year^{-1}$ [unchanged from (2)]. Currently, the application of industrially fixed N fertilizer is 112 Tg of N $year^{-1}$ (80). Quantification of anthropogenic biological N fixation in connection with agriculture is highly uncertain, but the most recent estimates are in the range of ~30 to 70 Tg of N $year^{-1}$ (81–83). According to Food and Agriculture Organization (84), the total introduction of anthropogenically fixed N applied to the agricultural system is ~190 Tg $year^{-1}$ so this boundary is also globally transgressed.").

[294] United Nations Environment Programme & Food and Agriculture Organization of the United Nations (2024) GLOBAL NITROUS OXIDE ASSESSMENT, 93 ("Nitrogen oxides emissions lead to multiple changes in climate drivers in the troposphere, including increased tropospheric ozone, which causes warming; reductions in methane, due to increased formation of the oxidising hydroxyl radical, that causes cooling; and increases in both nitrate and secondary organic aerosols, which cause cooling. Ammonia emissions lead to increases in aerosols as well, causing cooling. Hence, while the direct impact of nitrous oxide reductions would be cooling, given that nitrous oxide is a powerful greenhouse gas, decreases in co-emissions primarily cause warming, often described as unmasking of greenhouse gas-induced warming due to reductions in cooling aerosols. In response to changes in emissions, the aerosols, ozone and methane responses would be rapid whereas changes in nitrous oxide would take place slowly over a century."); 95 ("Both nitrate and secondary organic aerosols would be expected to decrease because of the emissions reductions, the former due to a decrease in precursor nitrogen species and the latter due to a reduction in atmospheric oxidation capacity in response to cuts in nitrogen oxides. There are also small decreases in sulphate aerosols as their formation also slows in response to decreased oxidation capacity."); 95–96 ("As noted, the aerosol changes would be predominantly driven by changes in emissions from the agricultural sector, which is responsible for around 95 per cent of the reduction in ammonia emissions that dominates aerosol forcing. In contrast, emissions reductions in the industrial sector targeting nitrous oxide would not be expected to drive substantial aerosol changes[.]"). *See also* Gong C., *et al.* (2024) *Global net climate effects of anthropogenic reactive nitrogen*, NATURE 632(8025): 557–563, 560–561 ("Figure 4a showed that the net climate effects derived from agricultural and non-agricultural sources were comparable (−0.19 [−0.03, −0.38] and −0.19 [−0.11, −0.31] W m^{-2}, respectively). For the agricultural sources, the net cooling effect was dominated by the direct aerosol effect, which could be attributed to the agricultural NH_3 emissions, whereas the Nr effects of CO_2 uptake and N_2O emissions on the global radiative forcing compensated each other, in agreement with previous studies[9]. Conversely, NO_x emissions emitted from fossil fuel combustion dominated the net cooling effects of non-agricultural sources. Higher atmospheric NO_x burden not only induced a higher nitrate aerosol burden but also significantly decreased the atmospheric mole fraction of CH_4 through increasing atmospheric OH.").

[295] United Nations Environment Programme & Food and Agriculture Organization of the United Nations (2024) GLOBAL NITROUS OXIDE ASSESSMENT, 97 ("Looking out to longer timescales and assuming other factors are constant after 2050, at the levels of the technical reductions and societal change scenario, comparing the technical reductions scenario (SSP1-2.6) with the highest nitrous oxide baseline among the marker SSP scenarios (SSP3-7.0), the nitrous oxide forcing becomes -0.20 (± 0.03) W/m^2 by 2100, driving the total 2100 radiative forcing to near zero … Accounting for the small additional methane lifetime feedback associated with continued nitrous oxide changes after 2050, the net in this case becomes negative in the 2090s even without methane reductions from livestock, whereas if becomes negative around 2070 if those methane reductions are included (Figure 4). Hence the near-term increased warming due to nitrogen management measures is likely to be replaced by longer-term reductions in warming although the timing and magnitude of such a transition is dependent upon the assumed reference case, the degree of nitrous oxide reductions achieve, and the timing and magnitude of continued reductions in ammonia emissions after 2050."); 173 ("Ambitious nitrous oxide abatement under a sustainable nitrogen management approach will initially generate significant benefits for air quality, which in turn will avoid millions of premature deaths. Meanwhile, the climate and ozone-layer benefits of ambitious abatement will be felt towards the second half of the 21st century, including avoided skin cancers, cataracts and carbon dioxide emissions. These benefits will increase with time. In all cases, delivering these benefits requires starting ambitious nitrous oxide abatement now.").

[296] Stein L. Y. & Lidstrom M. E. (2024) *Greenhouse gas mitigation requires caution*, SCIENCE 384(6700): 1068–1069, 1068 ("Methane (CH_4) and nitrous oxide (N_2O) are greenhouse gases that rank second and third behind carbon dioxide (CO_2) as primary contributors to global warming and climate change. Outside of fossil sources, these gases are emitted by microorganisms as they interact with their environment. Many strategies have targeted reduction of methane emissions. Although such efforts are well meaning, the microbial communities that live in these settings can respond to mitigation efforts by producing more N_2O, which reduces or even negates the positive climate impact (1, 2). Mitigation approaches too often have not accounted for these trade-offs, and doing so requires additional monitoring to make sure any specific strategy achieves a net climate benefit.").

[297] Stein L. Y. & Lidstrom M. E. (2024) *Greenhouse gas mitigation requires caution*, SCIENCE 384(6700): 1068–1069, 1068 ("Synthetic or biological amendments aimed at inhibiting microbial communities that convert ammonia to nitrate (nitrifying communities) can reduce N_2O emissions (4). However, many classes of nitrification inhibitors (NIs) will also inhibit methanotrophs, potentially increasing CH_4 emissions. Conversely, in the anoxic zone, methanogens produce CH_4, but some anaerobic methanotrophs consume CH4 and reduce NO_3^- or NO_2^- without N_2O release. Promising biology-based CH_4 mitigation technologies under development include CH_4 biofilters both as open treatment systems and closed bioreactors, bioconversion of CH_4 into protein and bioplastics, and development of biocontrol treatments to reduce CH_4 production in rice paddy and landfill soils and in ruminants (5). Each strategy has an impact on the N cycle, including the possibility of increasing N_2O emissions. Using porous biocovers such as compost, for example, to decrease CH_4 emissions by enhancing aerobic methanotroph-mediated CH_4 consumption unfortunately resulted in increased N_2O emissions (6). Instead, biocovers enriched in iron and copper might simultaneously reduce N_2O and CH_4 emissions by relieving essential nutrient limitations."); 1069 ("Biology-based strategies under development to mitigate N_2O emissions include crop amendments such as biofertilizers, biological nitrification inhibitors, biopesticides, and biochar (14). Changes to management practices such as timed irrigation and fertilization and reduced tillage are effective means to reduce N_2O emissions by reducing N loading and excessive disturbance of the soil. However, analysis of these strategies does not always take CH_4 emissions into account. Determining if crop amendments can stimulate microbial N_2O removal is currently being investigated (15).").

[298] United Nations Environment Programme & Food and Agriculture Organization of the United Nations (2024) GLOBAL NITROUS OXIDE ASSESSMENT, 25, 153 ("There is a considerable risk that increasing the use of ammonia as a fuel for marine shipping and biofuels derived from fertilised crops could produce significant nitrous oxide emissions, partially or completely offsetting their intended climate benefits. For example, recent studies suggest that nitrous oxide emissions from the use of ammonia as a shipping fuel could, if not managed properly, exceed agricultural nitrous oxide emissions."; "Tradeoffs and synergies with other pollutant mitigation efforts must be considered (Montes et al. 2013; Sajeev et al. 2018; Rivera and Chará 2021). Nitrous oxide and ammonia emissions can be reduced by, for example, lowering the crude protein content in animal feed, but that may also increase methane emissions from

ruminants. Manure aeration, covering manure during storage and air scrubbers in animal housing but increase those from nitrous oxide.”).

[299] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS, Figure 5.1.

[300] United Nations Environment Programme & World Meteorological Organization (2011) INTEGRATED ASSESSMENT OF BLACK CARBON AND TROPOSPHERIC OZONE, 254, 262 (“Evaluating global mean temperature change, it was found that the targeted measures to reduce emissions of methane and BC could greatly reduce warming rates over the next few decades (Figure 6.1; Box 6.1). When all measures are fully implemented, warming during the 2030s relative to the present would be only half as much as in the reference scenario. In contrast, even a fairly aggressive strategy to reduce CO_2 emissions, as for the CO_2-measures scenario, does little to mitigate warming until after the next 20-30 years (Box 6.2). … Large impacts of the measures examined here were also seen for the Arctic despite the minimal amount of emissions currently taking place there. This occurs due to the high sensitivity of the Arctic both to pollutants that are transported there from remote sources and to radiative forcing that takes place in areas of the northern hemisphere outside the Arctic. The 16 measures examined here, including the measures on pellet stoves and coal briquettes, reduce warming in the Arctic by 0.7 ºC (range 0.2 to 1.3 ºC) at 2040. This is a large portion of the 1.1 ºC (range 0.7 to 1.7 ºC) warming projected under the reference scenario for the Arctic, and hence implementation of the measures would be virtually certain to substantially slow, but not halt, the pace of Arctic climate change.”).

[301] Sand M., Berntsen T. K., Seland Ø., & Kristjánsson J. E. (2013) *Arctic surface temperature change to emissions of black carbon within Arctic or midlatitudes*, J. GEOPHYS. RES. 118(14): 7788–7798, 7788 (“The climate model includes a snow model to simulate the climate effect of BC deposited on snow. We find that BC emitted within the Arctic has an almost five times larger Arctic surface temperature response (per unit of emitted mass) compared to emissions at midlatitudes. Especially during winter, BC emitted in North-Eurasia is transported into the high Arctic at low altitudes. A large fraction of the surface temperature response from BC is due to increased absorption when BC is deposited on snow and sea ice with associated feedbacks.”). *See also* Stohl A., Klimont Z., Eckhardt S., Kupiainen K., Shevchenko V. P., Kopeikin V. M., & Novigatsky A. N. (2013) *Black carbon in the Arctic: the underestimated role of gas flaring and residential combustion emissions*, ATMOS. CHEM. PHYS. 13(17): 8833–8855, 8848 (Fig. 9. Time series of measured EBC and carbon monoxide as well as modeled BC split into different source categories for the Zeppelin station for the period 12 February until 4 March 2010.).

[302] Qian Y., Yasunari T. J., Doherty S. J., Flanner M. G., Lau W. K. M., Ming J., Wang H., Wang M., Warren S. G., & Zhang R. (2014) *Light-absorbing Particles in Snow and Ice: Measurement and Modeling of Climatic and Hydrological impact*, ADV. ATMOS. SCI. 32: 64–91, 64 (“Light absorbing particles (LAP, e.g., black carbon, brown carbon, and dust) influence water and energy budgets of the atmosphere and snowpack in multiple ways. In addition to their effects associated with atmospheric heating by absorption of solar radiation and interactions with clouds, LAP in snow on land and ice can reduce the surface reflectance (a.k.a., surface darkening), which is likely to accelerate the snow aging process and further reduces snow albedo and increases the speed of snowpack melt. LAP in snow and ice (LAPSI) has been identified as one of major forcings affecting climate change, e.g. in the fourth and fifth assessment reports of IPCC. However, the uncertainty level in quantifying this effect remains very high. In this review paper, we document various technical methods of measuring LAPSI and review the progress made in measuring the LAPSI in Arctic, Tibetan Plateau and other mid-latitude regions. We also report the progress in modeling the mass concentrations, albedo reduction, radiative forcing, and climatic and hydrological impact of LAPSI at global and regional scales. Finally we identify some research needs for reducing the uncertainties in the impact of LAPSI on global and regional climate and the hydrological cycle.”). *See also* Arctic Monitoring and Assessment Programme (2017) ADAPTATION ACTIONS FOR A CHANGING ARCTIC: PERSPECTIVES FROM THE BARENTS AREA, 72 (“Highly reflective surfaces, such as snow and ice in the Arctic increase light absorption by BC particles in the atmosphere. BC also absorbs light after deposition onto (and then into) snow and ice, where it accelerates the melt process (Pedersen et al., 2015). BC has made an important contribution to the observed rise in Arctic surface temperature through the 20th century (although carbon dioxide is still the major factor driving the rise in Arctic temperature) (Quinn et al., 2008; Koch et al., 2011; AMAP, 2015a). It may be technically possible to reduce global anthropogenic BC emissions by up to 75% by 2030 (Shindell et al., 2012; AMAP, 2015a; Stohl et al., 2015). As well as helping to slow warming,

BC emission reductions would also have significant health benefits (Anenberg et al., 2012; Shindell et al., 2012)."); International Energy Agency (2016) WORLD ENERGY OUTLOOK SPECIAL REPORT: ENERGY AND AIR POLLUTION, 115 ("Two areas of clear cross-benefit (for air quality and climate change) are actions to reduce emissions of black carbon, a major component of PM, and of methane (Box 3.4). Black carbon – emitted due to incomplete combustion, particularly from household biomass stoves and diesel vehicles – affects the climate in multiple ways. It absorbs incoming sunlight, leading to warming in the atmosphere, settles on the ground accelerating the melting of Arctic and alpine ice and, along with other pollutants that form aerosols, it affects the formation of clouds, so having a knock-on influence on increased warming."); *and* World Bank & International Cryosphere Climate Initiative (2013) ON THIN ICE: HOW CUTTING POLLUTION CAN SLOW WARMING AND SAVE LIVES, 2 ("Climate benefits for cryosphere regions from black carbon reductions carry less uncertainty than they would in other parts of the globe and are sometimes very large. This is because emissions from sources that emit black carbon—even with other pollutants—almost always lead to warming over reflective ice and snow.").

[303] While this section focuses on warming from black carbon emitted by increased shipping in the Arctic, we note that use of high-sulfur heavy fuel oil in shipping has historically also contributed to sulfate aerosols and the formation of reflective ship tracks. The IMO has adopted regulations limiting sulfur content of shipping fuels, resulting in reduced cooling from sulfates and ship tracks. *See* Hansen J. E., Sato M., Simons L., Nazarenko L. S., Sangha I., Kharecha P., Zachos J. C., von Schuckmann K., Loeb N. G., Osman M. B., Jin Q., Tselioudis G., Jeong E., Lacis A., Ruedy R., Russell G., Cao J., & Li J. (2023) *Global warming in the pipeline*, OXF. OPEN CLIM. CHANGE 3(1): 1–33,, 18–19 ("Changes of IMO emission regulations provide a great opportunity for insight into aerosol climate forcing. Sulfur content of fuels was limited to 1% in 2010 near the coasts of North America and in the North Sea, Baltic Sea and English Channel, and further restricted there to 0.1% in 2015 [163]. In 2020 a limit of 0.5% was imposed worldwide. The 1% limit did not have a noticeable effect on ship-tracks, but a striking reduction of ship-tracks was found after the 2015 IMO regulations, especially in the regions near land where emissions were specifically limited [164]. Following the additional 2020 regulations [165], global ship-tracks were reduced more than 50% [166]. Earth's albedo (reflectivity) measured by CERES (Clouds and Earth's Radiant Energy System) satellite-borne instruments [81] over the 22-years March 2000 to March 2022 reveal a decrease of albedo and thus an increase of absorbed solar energy coinciding with the 2015 change of IMO emission regulations.").

[304] International Maritime Organization (10–17 June 2021) *Marine Environment Protection Committee (MEPC 76)* ("The MEPC adopted amendments to MARPOL Annex I (addition of a new regulation 43A) to introduce a prohibition on the use and carriage for use as fuel of heavy fuel oil (HFO) by ships in Arctic waters on and after 1 July 2024. The prohibition will cover the use and carriage for use as fuel of oils having a density at 15°C higher than 900 kg/m^3 or a kinematic viscosity at 50°C higher than 180 mm^2/s. Ships engaged in securing the safety of ships, or in search and rescue operations, and ships dedicated to oil spill preparedness and response would be exempted. Ships which meet certain construction standards with regard to oil fuel tank protection would need to comply on and after 1 July 2029. A Party to MARPOL with a coastline bordering Arctic waters may temporarily waive the requirements for ships flying its flag while operating in waters subject to that Party's sovereignty or jurisdiction, up to 1 July 2029.").

[305] Comer B., Osipova L., Georgeff E., & Mao X. (2020) *The International Maritime Organization's proposed arctic heavy fuel oil ban: likely impacts and opportunities for improvement*, International Council on Clean Transportation, 2–3 ("HFO has already been banned in the Antarctic since 2011, without any exemptions or waivers. In the Antarctic, defined by the IMO's MARPOL Convention as a neat circle below 60°S latitude, ships are not only forbidden from using HFO and carrying HFO in their fuel tanks, they cannot even carry HFO as cargo or ballast. There is little commercial shipping activity in the Antarctic region, and this made the decision less contentious. The Arctic, meanwhile, has substantial amounts of commercial shipping activity, including fishing and the transport of oil, gas, and minerals from the region. The carriage and use of HFO is especially common for oil tankers, general cargo ships, and bulk carriers in the region, as we will show later in this analysis. The Arctic HFO ban, as currently proposed, would start to apply on July 1, 2024 and would forbid using or carrying HFO as fuel, but would allow HFO cargoes to be transported. In addition to the cargo exemption, the text of the HFO ban allows for exemptions and waivers, as follows."). *See also* Farand C. (3 September 2020) *Loopholes in Arctic heavy fuel oil ban defer action to the end of the decade*, CLIMATE HOME NEWS ("Burning and carrying HFO has been banned in Antarctic waters since 2011, but

plans for similar restrictions in the resource-rich Arctic have met with resistance. Russia, which could benefit from the opening of more shipping routes in the region as Arctic sea ice melts, is one of the most vocal opponents.").

[306] Comer B., Osipova L., Georgeff E., & Mao X. (2020) *The International Maritime Organization's proposed arctic heavy fuel oil ban: likely impacts and opportunities for improvement*, International Council on Clean Transportation, 10–11, 19 ("As shown in Figure 8, had the proposed HFO ban been in place in 2019, it would have banned just 30% of HFO carried as fuel and 16% of the HFO used by ships in the Arctic. Total BC emissions in the Arctic would have fallen by only 5% because the majority of HFO use would have been allowed by virtue of exemptions or waivers. Of the 700 HFO-fueled ships in the Arctic in 2019, 151, or 22% of the fleet, would have been exempt. Of these, 18 would have been eligible for a waiver had they not already been exempt. The flag state with the most exempt ships was Panama, with 31 ships, followed by Marshall Islands with 27, Liberia with 15, Russia with 11, and the Netherlands with 11. Other flag states had fewer than 10 ships exempt. An additional 366 ships, or 52% of the HFO-fueled fleet, would have been eligible for a waiver, including 325 ships flagged to Russia, 20 to Canada, 10 to Norway, 10 to Denmark, and one to the United States. Together, exemptions and waivers would have allowed 74% of the HFO-fueled fleet, by number of ships, to continue to use HFO in the Arctic.").

[307] Comer B., Osipova L., Georgeff E., & Mao X. (2020) *The International Maritime Organization's proposed arctic heavy fuel oil ban: likely impacts and opportunities for improvement*, International Council on Clean Transportation, 20 ("Moving down Figures 15, 16, and 17, the top bars show the HFO ban without exemptions or waivers, in which case 100% of HFO carriage and use would be banned and BC emissions would decrease by 30%.6 The second bars show that disallowing exemptions and limiting waivers only to IW results in banning 75% of HFO carriage and 82% of HFO use, which would cut BC emissions by 24%. The third bar in the figures shows the impact of allowing waivers in both IW and TS. In this case, 70% of HFO carriage and 75% of HFO use would be banned, and this would cut BC emissions by 22%. Figure 20 shows the location and amount of HFO used that would have been allowed in 2019 under this alternative. Comparing this with Figure 19 shows that HFO remains available for use near shore; this could allow for domestic transportation while banning HFO in the offshore areas. This alternative may strike a balance between allowing HFO to be carried and used for domestic shipping and community resupply while banning a significant amount of HFO carriage and use. However, an HFO spill close to shore would result in larger direct impacts to Arctic coastlines and coastal communities. The most protective alternative is a ban without exemptions and waivers.").

[308] Arctic Council (2019) EXPERT GROUP ON BLACK CARBON AND METHANE SUMMARY OF PROGRESS AND RECOMMENDATIONS 2019, 13 ("At their 2017 meeting the Ministers of the Arctic Council member states adopted an expert group report that recommended a collective, aspirational goal to further reduce black carbon emissions by 25-33 percent relative to 2013 levels by 2025. ").

[309] Organisation for Economic Co-operation and Development (April 2021) THE ECONOMIC BENEFITS OF AIR QUALITY IMPROVEMENTS IN ARCTIC COUNCIL COUNTRIES, 13 ("Additional policies to extensively adopt the best available techniques would allow Arctic Council countries to reduce their emissions more substantially an dhalve their black carbon emissions by 2025, exceeding their collective target.

[310] Organisation for Economic Co-operation and Development (April 2021) THE ECONOMIC BENEFITS OF AIR QUALITY IMPROVEMENTS IN ARCTIC COUNCIL COUNTRIES, 46 ("According to the projections for 2050, with existing policies (the CKLE scenario), 8% of the population living in Arctic Council countries would be exposed to concentration levels of $PM_{2.5}$ above the WHO guidelines. However, in the MTFR-AC scenario, only 1% would be exposed to these concentrations. This decrease I equivalent to a change from 18 million people in the MTFR-AC scenario.").

[311] International Maritime Organization (1 December 2021) *IMO moves ahead on GHG emissions, Black Carbon and marine litter* ("The International Maritime Organization (IMO) in view of the urgency for all sectors to accelerate their efforts to reduce GHG emissions - as emphasized in the recent IPCC reports and the Glasgow Climate Pact - recognized the need to strengthen the ambition of the Initial IMO GHG Strategy during its revision process. IMO's Marine Environment Protection Committee (MEPC), meeting virtually for its 77th session, 22-26 November 2021,

agreed to initiate the revision of its GHG strategy. The MEPC also adopted a resolution on voluntary use of cleaner fuels in the Arctic, to reduce black carbon emissions. In other work, the MEPC adopted a strategy to address marine plastic litter from ships; adopted revised guidelines for exhaust gas cleaning systems (EGCS) and agreed the scope of work on discharge water of EGCS; and considered matters related to the Ballast Water Management Convention."). *See also* Humpert M. (6 December 2021) *IMO adopts new measures to reduce black carbon in Arctic shipping*, ARCTICTODAY.

[312] Guzman J. (1 December 2020) *Every major US bank has now come out against Arctic drilling*, THE HILL ("Goldman Sachs, Morgan Stanley, Chase, Wells Fargo and CitiBank announced commitments not to finance oil and gas projects in the Arctic National Wildlife Refuge (ANWR) earlier this year.").

[313] Tabuchi H. (3 February 2024) *Bank of America Pledged to Stop Financing Coal. Now It's Backtracking*, THE NEW YORK TIMES ("Two years ago, Bank of America won kudos from climate activists for saying it would no longer finance new coal mines, coal-burning power plants or Arctic drilling projects because of the toll they take on the environment. The bank's latest environment and social-risk policy reneged on those commitments. The policy, updated in December, says that such projects will instead be subject to "enhanced due diligence." Bank of America's change follows intensifying backlash from Republican lawmakers against corporations that consider environmental and social factors in their operations.").

[314] Marsh A. & Dlouhy J. A. (19 November 2020) *Arctic Oil Fight Comes to Insurers as Trump Plans Lease Sale*, BLOOMBERG GREEN.

[315] Desch S. J., Smith N., Groppi C., Vargas P., Jackson R., Kalyaan A., Nguyen P., Probst L., Rubin M. E., Singleton H., Spacek A., Truitt A., Zaw P. P., & Hartnett H. E. (2017) *Arctic ice management*, EARTH'S FUTURE 5: 107–27, 107 ("Here we investigate a means for enhancing Arctic sea ice production by using wind power during the Arctic winter to pump water to the surface, where it will freeze more rapidly. We show that where appropriate devices are employed, it is possible to increase ice thickness above natural levels, by about 1 m over the course of the winter. We examine the effects this has in the Arctic climate, concluding that deployment over 10% of the Arctic, especially where ice survival is marginal, could more than reverse current trends of ice loss in the Arctic, using existing industrial capacity. We propose that winter ice thickening by wind-powered pumps be considered and assessed as part of a multipronged strategy for restoring sea ice and arresting the strongest feedbacks in the climate system."). *See also* Field L., Ivanova D., Bhattacharyya S., Mlaker V., Sholtz A., Decca R., Manzara A., Johnson D., Christodoulou E., Walter P., & Katuri K. (2018) *Increasing Arctic Sea Ice Albedo Using Localized Reversible Geoengineering*, EARTH'S FUTURE 6(6): 882–901 (discussing testing hollow silica beads to enhance albedo of Arctic sea ice); Bodansky D. & Hunt H. (2020) *Arctic Climate Interventions*, INT. J. MAR. COAST. LAW 35(3): 596–617, 605–606 ("Arctic ice management focuses on saving Arctic ice directly, either by increasing the rate of freezing or by decreasing the rate of melting. One proposed technique to increase freezing would be to spray seawater directly on top of the ice during the Arctic winter, when despite global warming it is still generally very cold.[41] Ice is an insulator and slows the freezing of the water beneath it. Pumping water from under sea ice and spraying it on top, where it would be directly exposed to frigid air, would thus increase the rate of freezing and result in thicker ice… A second option focuses on decreasing the rate of melting of Arctic ice by spraying reflective beads on top of the ice in order to increase its albedo.[43]"); *and* Real Ice, *Re-Icing Approach* (*last visited* 25 March 2024) ("By increasing the thickness of the ice we also increase the surface albedo level (Reflectivity) which allows for more reflection of solar radiation or 'cooling' during the summer months. If we can bring the level of the sea ice to above a minimum, we can expect the sea ice to remain through the summer months to the following winter. The innovation brought forward by Real Ice is in the combination of pumping technology, already used by many today, with the advancements made in the renewables and clean energy sector. We are using this to create a system that can be run solely from renewable energy sources and our primary challenge is to demonstrate the capability to scale this methodology. … [O]ur method for re-icing would be achieved by pumping sea water on top of existing ice, during the winter season, to accelerate the thickening of ice. Water pumps would be zero-emission and would be fuelled by renewable energy. We call this method AquaFreezing.").

[316] Ocean Visions (16 September 2024) *First-ever assessment of pathways to slow Arctic sea ice loss identifies potential mitigation approaches and highlights need to increase collaborative, careful research*, Press Release ("The

Arctic Sea Ice Road Map reviews 21 different approaches in five main categories of action: Arctic Protection; Pollution Management; Ice Management; Surface Albedo Modification; and Solar Radiation Modification. The map synthesizes and summarizes the available information on all potential pathways, categorizes approaches by their application (regionally versus globally), their potential impact, reversibility, potential costs, and governance and justice considerations, and spotlights the highest priorities for additional research. The road map reinforces the importance of accelerating and scaling up investment into must-have actions – including global greenhouse gas emissions reductions, especially methane, carbon dioxide removal, and reducing localized black carbon emissions caused by shipping and wildland fires.").

[317] Canadell J. G., *et al.* (2021) *Chapter 5: Global Carbon and other Biogeochemical Cycles and Feedbacks*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), FAQ 5.1, 771 ("For decades, about half of the carbon dioxide (CO_2) that human activities have emitted to the atmosphere has been taken up by natural carbon sinks in vegetation, soils and oceans. These natural sinks of CO_2 have thus roughly halved the rate at which atmospheric CO_2 concentrations have increased, and therefore slowed down global warming. However, observations show that the processes underlying this uptake are beginning to respond to increasing CO_2 in the atmosphere and climate change in a way that will weaken nature's capacity to take up CO_2 in the future."). *See also* Joos F., *et al.* (2013) *Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: a multi-model analysis*, ATMOS. CHEM. PHYS. 13(5): 2793–2825, 2804 (Figure 1a); *and* Archer D., Eby M., Brovkin V., Ridgwell A., Cao L., Mikolajewicz U., Caldeira K., Matsumoto K., Munhoven G., Montenegro A., & Tokos K. (2009) *Atmospheric Lifetime of Fossil Fuel Carbon Dioxide*, ANNU. REV. EARTH PLANET. SCI. 37: 117–134, 121 ("Finally, the 2007 IPCC report removed the table from the "Policymaker Summary," and added in the "Executive Summary" of Chapter 7 on the carbon cycle, "About half of a CO_2 pulse to the atmosphere is removed over a timescale of 30 years; a further 30% is removed within a few centuries; and the remaining 20% will typically stay in the atmosphere for many thousands of years" (Denman et al 2007, page 501).").

[318] Jones C. D., Frölicher T. L., Koven C., MacDougall A. H., Matthews H. D., Zickfeld K., Rogelj J., Tokarska K. B., Gillett N. P., Ilyina T., Meinshausen M., Mengis N., Séférian R., Eby M., & Burger F. A. (2019) *The Zero Emissions Commitment Model Intercomparison Project (ZECMIP) contribution to C4MIP: quantifying committed climate changes following zero carbon emissions*, GEOSCI. MODEL DEV. 12(10): 4375–4385, 4375 ("The zero emissions commitment (ZEC), or the amount of global mean temperature change that is still expected to occur after a complete cessation of CO_2 emissions, is a key component of estimating the remaining carbon budget to stay within global warming targets as well as an important metric to understand impacts and reversibility of climate change (Matthews and Solomon, 2013). Much effort is put into measuring and constraining the TCRE – the Transient Climate Response to cumulative CO_2 Emissions (Allen et al., 2009; Matthews et al., 2009; Zickfeld et al., 2009; Raupach et al., 2011; Gillett et al., 2013; Tachiiri et al., 2015; Goodwin et al., 2015; Steinacher and Joos, 2016; MacDougall, 2016; Ehlert et al., 2017; Millar and Friedlingstein, 2018). The TCRE describes the ratio between CO_2-induced warming and cumulative CO_2 emissions up to the same point in time, but it does not capture any delayed warming response to CO_2 emissions beyond the point that emissions reach zero. When using the TCRE to derive the carbon budget consistent with a specific temperature limit, the ZEC is often assumed to be negligible and close to zero (Matthews et al., 2017; Rogelj et al., 2011, 2018). Constraints on ZEC have not been systematically researched so far, although both TCRE and ZEC are required to relate carbon emissions to the eventual equilibrium warming (Rogelj et al., 2018). It has been shown that continued CO_2 removal by natural sinks following cessation of emissions offsets the continued warming that would result from stabilized CO_2 concentration (Matthews and Caldeira, 2008; Solomon et al., 2009; Frölicher and Joos, 2010; Matthews and Weaver, 2010; Joos et al., 2013). This is partly due to the ocean uptake of both heat and carbon sharing some similar processes and timescales, and it is therefore expected to lead to ZEC being small (Allen et al., 2018; Ehlert and Zickfeld, 2017; Gillett et al., 2011; Matthews and Zickfeld, 2012)… More detailed studies, however, have shown that ZEC can be (a) nonzero, possibly of either positive or negative sign that may change in time during the period following emissions ceasing (Frölicher et al., 2014; Frölicher and Paynter, 2015), and (b) it is both state and rate dependent – i.e. it varies depending on the amount of carbon emitted and taken up by the natural carbon sinks, and the CO_2 emissions pathway of its emissions prior to cessation (Ehlert and Zickfeld, 2017; Krasting et al., 2014; MacDougall, 2019).").

[319] Lovejoy T. E. & Nobre C. (2018) *Amazon's Tipping Point*, SCI. ADV. 4(2): 1 ("We believe that negative synergies between deforestation, climate change, and widespread use of fire indicate a tipping point for the Amazon system to flip to nonforest ecosystems in eastern, southern and central Amazonia at 20–25% deforestation."). *See also* Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, REV. GEOPHYS. 61(e2021RG000757): 1–81, 28 ("Ultimately, current research cannot eliminate the possibility that changes across the boreal zone due to a warming climate could act as a net positive climate feedback, thanks to the potential for permafrost thaw and wildfires to liberate the soil carbon that makes up the majority of stored carbon across this ecosystem. Consequently, boreal forest dieback and shifts represent one of the more potentially immediate and significant climate system tipping elements (Table 7).").

[320] Griscom B. W., *et al*. (2017) *Natural climate solutions*, PROC. NAT'L. ACAD. SCI. 114(44): 11645–11650, 11645 ("Better stewardship of land is needed to achieve the Paris Climate Agreement goal of holding warming to below 2 °C; however, confusion persists about the specific set of land stewardship options available and their mitigation potential. To address this, we identify and quantify "natural climate solutions" (NCS): 20 conservation, restoration, and improved land management actions that increase carbon storage and/or avoid greenhouse gas emissions across global forests, wetlands, grasslands, and agricultural lands. We find that the maximum potential of NCS—when constrained by food security, fiber security, and biodiversity conservation—is 23.8 petagrams of CO_2 equivalent ($PgCO_2e$) y^{-1} (95% CI 20.3–37.4). This is ≥30% higher than prior estimates, which did not include the full range of options and safeguards considered here. About half of this maximum (11.3 $PgCO_2e$ y^{-1}) represents cost-effective climate mitigation, assuming the social cost of CO_2 pollution is ≥100 USD $MgCO_2e^{-1}$ by 2030. Natural climate solutions can provide 37% of cost-effective CO_2 mitigation needed through 2030 for a >66% chance of holding warming to below 2 °C. One-third of this cost-effective NCS mitigation can be delivered at or below 10 USD $MgCO_2^{-1}$. Most NCS actions—if effectively implemented—also offer water filtration, flood buffering, soil health, biodiversity habitat, and enhanced climate resilience. Work remains to better constrain uncertainty of NCS mitigation estimates. Nevertheless, existing knowledge reported here provides a robust basis for immediate global action to improve ecosystem stewardship as a major solution to climate change."). *See also* Moomaw W. R., Masino S. A., & Faison E. K. (2019) *Intact Forests in the Unites States: Proforestation Mitigates Climate Change and Serves the Greatest Good*, Perspective, FRONT. FOR. GLOB. CHANGE 2(27): 1–10, 1 ("Climate change and loss of biodiversity are widely recognized as the foremost environmental challenges of our time. Forests annually sequester large quantities of atmospheric carbon dioxide (CO_2), and store carbon above and below ground for long periods of time. Intact forests—largely free from human intervention except primarily for trails and hazard removals—are the most carbon-dense and biodiverse terrestrial ecosystems, with additional benefits to society and the economy. … The recent *1.5 Degree Warming Report* by the Intergovernmental Panel on Climate Change identifies *reforestation* and *afforestation* as important strategies to increase negative emissions, but they face significant challenges: afforestation requires an enormous amount of additional land, and neither strategy can remove sufficient carbon by growing young trees during the critical next decade(s). In contrast, growing existing forests intact to their ecological potential—termed *proforestation*—is a more effective, immediate, and low-cost approach that could be mobilized across suitable forests of all types. Proforestation serves the greatest public good by maximizing co-benefits such as nature-based biological carbon sequestration and unparalleled ecosystem services such as biodiversity enhancement, water and air quality, flood and erosion control, public health benefits, low impact recreation, and scenic beauty."); *and* World Wildlife Fund (2020) *Living Planet Report 2020 – Bending the curve of biodiversity loss*, Almond R. E. A., Grooten M., & Petersen T. (eds.), 6 ("The global Living Planet Index continues to decline. It shows an average 68% decrease in population sizes of mammals, birds, amphibians, reptiles and fish between 1970 and 2016. … It matters because biodiversity is fundamental to human life on Earth, and the evidence is unequivocal – it is being destroyed by us at a rate unprecedented in history. Since the industrial revolution, human activities have increasingly destroyed and degraded forests, grasslands, wetlands and other important ecosystems, threatening human well-being. Seventy-five per cent of the Earth's ice-free land surface has already been significantly altered, most of the oceans are polluted, and more than 85% of the area of wetlands has been lost.").

[321] Bloomer L., Sun X., Dreyfus G., Ferris T., Zaelke D., & Schiff C. (2022) *A Call to Stop Burning Trees in the Name of Climate Mitigation*, VT. J. ENVT'L. LAW 23: 94–123, 94 ("Burning trees for energy delivers a one-two punch against climate change mitigation efforts. Harvesting woody biomass reduces the sequestration potential of forest carbon

sinks, while the combustion of woody biomass releases large quantities of carbon into the air.[1] Forest regrowth may not offset these emissions for many decades[2]—well beyond the time the world has left to slow warming to avoid catastrophic impacts from climate change."). *See also* Raven P., *et al.* (11 February 2021) *Letter Regarding Use of Forests for Bioenergy*, WOODWELL CLIMATE RESEARCH CENTER ("Trees are more valuable alive than dead both for climate and for biodiversity. To meet future net zero emission goals, your governments should work to preserve and restore forests and not to burn them.").

[322] Rockström J., Beringer T., Hole D., Griscom B., Mascia M. B., Folke C., & Creutzig F. (2021) *We Need Biosphere Stewardship That Protects Carbon Sinks and Builds Resilience*, PROC. NAT'L. ACAD. SCI. 118(38): 1–8, 2 ("Using the reduced complexity climate model MAGICC6 ("Model for the Assessment of Greenhouse Gas Induced Climate Change Version 6"), we examined changes in global mean temperature up till now and in the future under the RCP2.6 emission scenario—the only emission pathway that aligns with the Paris agreement—but assumed that ecosystems on land had stopped absorbing CO_2 from 1900 onwards. In such a world, global temperatures would have risen much faster (Fig. 1C, red line). In fact, we would have already crossed the 1.5 °C threshold, demonstrating that terrestrial ecosystems have reduced warming by at least 0.4 °C since 1900.").

[323] Duffy K. A., Schwalm C. R., Arcus V. L., Koch G. W., Liang L. L., & Schipper L. A. (2021) *How close are we to the temperature tipping point of the terrestrial biosphere?*, SCI. ADV. 7(3): 1–8, 1 ("The temperature dependence of global photosynthesis and respiration determine land carbon sink strength. While the land sink currently mitigates ~30% of anthropogenic carbon emissions, it is unclear whether this ecosystem service will persist and, more specifically, what hard temperature limits, if any, regulate carbon uptake. Here, we use the largest continuous carbon flux monitoring network to construct the first observationally derived temperature response curves for global land carbon uptake. We show that the mean temperature of the warmest quarter (3-month period) passed the thermal maximum for photosynthesis during the past decade. At higher temperatures, respiration rates continue to rise in contrast to sharply declining rates of photosynthesis. Under business-as-usual emissions, this divergence elicits a near halving of the land sink strength by as early as 2040."). *See also* Hubau W., *et al.* (2020) *Asynchronous carbon sink saturation in African and Amazonian tropical forests*, NATURE 579: 80–87, 85 ("In summary, our results indicate that although intact tropical forests remain major stores of carbon and are key centres of biodiversity11, their ability to sequester additional carbon in trees is waning. In the 1990s intact tropical forests removed 17% of anthropogenic CO_2 emissions. This declined to an estimated 6% in the 2010s, because the pan-tropical weighted average per unit area sink strength declined by 33%, forest area decreased by 19% and anthropogenic CO_2 emissions increased by 46%. Although tropical forests are more immediately threatened by deforestation46 and degradation[47], and the future carbon balance will also depend on secondary forest dynamics[48] and forest restoration plans[49], our analyses show that they are also affected by atmospheric chemistry and climatic changes. Given that the intact tropical forest carbon sink is set to end sooner than even the most pessimistic climate driven vegetation models predict[4,5], our analyses suggest that climate change impacts in the tropics may become more severe than predicted. Furthermore, the carbon balance of intact tropical forests will only stabilize once CO_2 concentrations and the climate stabilizes."); *and* Intergovernmental Panel on Climate Change (2021) *Summary for Policymakers*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 20 ("Based on model projections, under the intermediate scenario that stabilizes atmospheric CO_2 concentrations this century (SSP2-4.5), the rates of CO_2 taken up by the land and oceans are projected to decrease in the second half of the 21st century (*high confidence*). Under the very low and low GHG emissions scenarios (SSP1-1.9, SSP1-2.6), where CO_2 concentrations peak and decline during the 21[st] century, land and oceans begin to take up less carbon in response to declining atmospheric CO_2 concentrations (*high confidence*) and turn into a weak net source by 2100 under SSP1-1.9 (*medium confidence*). It is very unlikely that the combined global land and ocean sink will turn into a source by 2100 under scenarios without net negative emissions[32] (SSP2-4.5, SSP3-7.0, SSP5-8.5). … Additional ecosystem responses to warming not yet fully included in climate models, such as CO_2 and CH_4 fluxes from wetlands, permafrost thaw and wildfires, would further increase concentrations of these gases in the atmosphere (*high confidence*).").

[324] Duffy K. A., Schwalm C. R., Arcus V. L., Koch G. W., Liang L. L., & Schipper L. A. (2021) *How close are we to the temperature tipping point of the terrestrial biosphere?*, SCI. ADV. 7(3): 1–8, 3 ("This…calls into question the future viability of the land sink, along with Intended Nationally Determined Contributions (INDCs) within the Paris

Climate Accord, as these rely heavily on land uptake of carbon to meet pledges. In contrast to Representative Concentration Pathway 8.5 (RCP8.5), warming associated with scenario RCP2.6 could allow for near-current levels of biosphere productivity, preserving the majority land carbon uptake (~10 to 30% loss).”). *See also* Rockström J., Beringer T., Hole D., Griscom B., Mascia M. B., Folke C., & Creutzig F. (2021) *We Need Biosphere Stewardship That Protects Carbon Sinks and Builds Resilience*, PROC. NAT'L. ACAD. SCI. 118(38): 1–8, 1–2 (“All major global climate models whose simulations give us hope of meeting the target of the Paris Climate Agreement—to keep warming well below 2 °C—take the continued provision of this gigantic biosphere endowment for granted, merely concluding, as in the recent IPCC report, that the efficiency of nature’s carbon sink may reduce slightly for high emission pathways. This means that the ability of intact nature to continue to sequester carbon is already factored into the climate models and thus in the estimate of the remaining carbon budget to hold to the Paris climate target. Yet this fundamental assumption relies on terrestrial and marine ecosystems remaining sufficiently intact and resilient to human pressures, even as climate change progresses (3). It is therefore concerning that the IPCC now concludes that Earth’s temperature is slightly more sensitive to rising CO_2 concentrations than previously thought (4)—meaning our remaining carbon budget to achieve the Paris target may have effectively shrunk. If we were able to more accurately simulate feedbacks in the global carbon cycle, such as tipping points in forest ecosystems (5) and abrupt permafrost thaw (6), the estimated remaining budget could disappear altogether.”).

[325] Canadell J. G., *et al.* (2021) *Chapter 5: Global Carbon and other Biogeochemical Cycles and Feedbacks*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), Table 5.6, 5-740 (“To estimate an upper limit on the impact of Amazon forest dieback on atmospheric CO_2, we consider the *very unlikely* limiting case of negligible direct-CO_2 effects (Section 5.4.1). Emergent constraint approaches (Section 5.4.6) may be used to estimate an overall loss of tropical land carbon due to climate change alone, of around 50 PgC per °C of tropical warming (Cox et al., 2013; Wenzel et al., 2014). This implies an upper limit to the release of tropical land carbon of <200 PgC over the 21st century (assuming tropical warming of <4°C and no CO_2-fertilization), which translates to $dCO_2/dt<0.5$ ppm yr^{-1}. Boreal forest dieback is not expected to change the atmospheric CO_2 concentration substantially because forest loss at the south is partly compensated by: (i) temperate forest invasion into previously boreal areas; and (ii) boreal forest gain at the north (Friend et al., 2014; Kicklighter et al., 2014; Schaphoff et al., 2016) (*medium confidence).* An upper estimate of this magnitude, based on statistical modelling of climate change alone, is of 27 Pg vegetation carbon loss in the southern boreal forest, which is roughly balanced by gains in the northern zone (Koven, 2013).”).*See also* Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, REV. GEOPHYS. 61: 1–81, 20 (“Strong evidence points toward an increasing frequency and severity of wildfires throughout the arctic and boreal north (Flannigan et al., 2009; Hanes et al., 2019; Kasischke & Turetsky, 2006; McCarty et al., 2020). Field observations have demonstrated that wildfire can act as a major driver of regional permafrost thaw, with fire contributing toward the expansion of thermokarst (areas where thaw leads to ground subsidence) area in western Canada (Gibson et al., 2018), Alaska (Y. Chen et al., 2021), and Siberia (Yanagiya & Furuya, 2020).”; Table 4).

[326] Cuadros A. (4 January 2023) *Has the Amazon Reached Its ‘Tipping Point’?*, THE NEW YORK TIMES (“For all the slashing and burning of recent years, the ecosystem still stores about 120 billion tons of carbon in its trunks, branches, vines and soil — the equivalent of about ten years of human emissions. If all of that carbon is released, it could warm the planet by as much as 0.3 degrees Celsius. According to the Princeton ecologist Stephen Pacala, this alone would probably make the Paris Agreement — the international accord to limit warming since preindustrial times to 2 degrees — “impossible to achieve.” Which, in turn, may mean that other climate tipping points are breached around the world. As the British scientist Tim Lenton put it to me, “The Amazon feeds back to everything.”).

[327] Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, REV. GEOPHYS. 61: 1–81, 24 (“Between the biomass in soil, permafrost, and living and dead vegetation, boreal forests represent a significant pool of terrestrial organic carbon (30% of global soil carbon) (Mcguire et al., 2009; Turetsky et al., 2019), and constitute 30% of global forest area (Kasischke, 2000). Of this fraction, two-thirds of boreal forest are found within Russia, with Russia's boreal forests estimated to contribute around half (0.6 Gt C/yr) of the total global

terrestrial carbon sink (Dolman et al., 2012; Schaphoff et al., 2013). Recent research has proposed that boreal forest carbon stocks could be underestimated, with updated calculations suggesting that boreal regions hold more terrestrial carbon (Bradshaw & Warkentin, 2015) than tropical areas, which have been previously suggested to harbor the largest stock of carbon among all terrestrial biomes (Y. Pan et al., 2011).").

[328] Zhu L., Li W., Ciais P., He J., Cescatti A., Santoro M., Tanaka K., Cartus O., Zhao Z., Xu Y., Sun M., & Wang J. (2023) *Comparable biophysical and biogeochemical feedbacks on warming from tropical moist forest degradation*, NAT. GEOSCI. 16(3): 244–249, 245 ("In 2010, 24.1% of TMFs [Tropical Moist Forests] belonged to one of the four categories of degraded forest (Fig. 1d)."). 246 ("We find that the local daytime temperature in burned, isolated, edge and other degraded forests is significantly higher than that in the interior forests by 1.12 ± 0.75, 0.90 ± 1.15, 0.76 ± 0.75 and 0.25 ± 0.47 °C (mean ± s.d.), respectively (Fig. 2a). The mean LST [Land Surface Temperature] warming magnitude of all degraded forests is 0.78 ± 0.88 °C, equivalent to 18% of the warming effect of deforestation area (4.40 ± 2.67 °C; Fig. 2a)."). 247 ("We then estimate the biogeochemical warming effect of forest degradation on LST of the atmospheric CO_2 lost by degraded forests, using a transient climate response to cumulative carbon emissions metric (TCRE)40 (Methods). This approach allows us to compare the biogeochemical LST warming effect from CO_2 losses with the biophysical LST changes due to changes in the surface energy budget. The AGC deficit is equivalent to an LST increase of 0.026 ± 0.013 °C over tropical land areas, which is of comparable magnitude to the biophysical warming (0.022 ± 0.014 °C), illustrating the importance of considering both biophysical and biogeochemical effects when evaluating the full climate impacts of forest degradation (Methods and Supplementary Text 5.1).").

[329] Doughty C. E., *et al.* (2023) *Tropical forests are approaching critical temperature thresholds*, NATURE 621: 105–111, 111 ("The critical temperature beyond which photosynthetic machinery in tropical trees begins to fail averages approximately 46.7 °C (T_{crit})[1]. However, it remains unclear whether leaf temperatures experienced by tropical vegetation approach this threshold or soon will under climate change. Here we found that pantropical canopy temperatures independently triangulated from individual leaf thermocouples, pyrgeometers and remote sensing (ECOSTRESS) have midday peak temperatures of approximately 34 °C during dry periods, with a long high-temperature tail that can exceed 40 °C. Leaf thermocouple data from multiple sites across the tropics suggest that even within pixels of moderate temperatures, upper canopy leaves exceed T_{crit} 0.01% of the time. Furthermore, upper canopy leaf warming experiments (+2, 3 and 4 °C in Brazil, Puerto Rico and Australia, respectively) increased leaf temperatures non-linearly, with peak leaf temperatures exceeding T_{crit} 1.3% of the time (11% for more than 43.5 °C, and 0.3% for more than 49.9 °C). Using an empirical model incorporating these dynamics (validated with warming experiment data), we found that tropical forests can withstand up to a 3.9 ± 0.5 °C increase in air temperatures before a potential tipping point in metabolic function, but remaining uncertainty in the plasticity and range of T_{crit} in tropical trees and the effect of leaf death on tree death could drastically change this prediction. The 4.0 °C estimate is within the 'worst-case scenario' (representative concentration pathway (RCP) 8.5) of climate change predictions2 for tropical forests and therefore it is still within our power to decide (for example, by not taking the RCP 6.0 or 8.5 route) the fate of these critical realms of carbon, water and biodiversity[3,4]."), *discussed in* Pedersen L. (26 August 2023) *Tropical forests nearing critical temperatures thresholds*, PHYS.ORG.

[330] Jones M. W., Veraverbeke S., Andela N., Doerr S. H., Kolden C., Mataveli G., Pettinari M. L., Le Quéré C., Rosan T. M., Van Der Werf G. R., Van Wees D., & Abatzoglou J. T. (2024) *Global rise in forest fire emissions linked to climate change in the extratropics*, SCIENCE 386(6719): 1–12, 7 ("During 2001 to 2023, forest fire C emissions grew by 60% across all forest ecoregions globally, principally driven by trends in the extratropical pyromes (Fig. 3 and table S1). Forest BA and fire C emissions were redistributed from tropical and subtropical pyromes to extratropical pyromes (Fig. 5).")."). *See also* Tandon A. (21 October 2024) *Climate change almost wipes out decline in global area burned by wildfires* ("The study finds that climate change has driven an increase in burned area in most IPCC regions, with only eight of the 42 regions showing a decrease in burned area due to the changing climate. … Many regions have seen more than a 10% increase in burned area due to climate change alone, including all IPCC regions in Australia and several regions in South America, Siberia and North America, the study adds. The authors find that on average, climate change has driven a 16% increase in burned area globally and increased the probability of experiencing months with above-average global burned area by 22%. … Conversely, the authors find that changes in direct human forcing factors since the early industrial period have driven a 19.1% decrease in burned area."), *discussing* Burton C., *et al.* (2024) *Global burned area increasingly explained by climate change*, NAT. CLIM. CHANG.: 1–7.

[331] Jones M. W., Veraverbeke S., Andela N., Doerr S. H., Kolden C., Mataveli G., Pettinari M. L., Le Quéré C., Rosan T. M., Van Der Werf G. R., Van Wees D., & Abatzoglou J. T. (2024) *Global rise in forest fire emissions linked to climate change in the extratropics*, SCIENCE 386(6719): 1–12, 5–7 ("Forest fire C emissions increased in several of the pyromes between 2001 and 2023 (Fig. 3); however, the most notable trend was a 194% increase in fire C emissions in pyrome ExTropF2 (+116 Tg C $year^{-1}$; table S1). This large increase in fire C emissions was driven by a 167% increase in forest BA (+35 thousand km^2 $year^{-1}$) and a 58% increase in C combustion rate (C emissions per unit BA; Fig. 3 and table S1). Increased forest BA was a widespread feature of the ecoregions in pyrome ExTropF2, with over half showing significant increases and fewer than 5% showing significant decreases (Fig. 4 and fig. S11). Consequently, the increases in forest fire C emissions were also widespread. For example, forest fire C emissions increased significantly in parts of Russia (east and northeast Siberian taiga), Europe (e.g., Balkan mixed forests, Pindus and Dinaric mountains mixed forests), western North America (e.g., Sierra Nevada forests, North-Central Rockies forests, Muskwa-Slave lake forests, Fraser Plateau and Basin complex, and Northwest Territories taiga), Chile (Valdivian temperate forests), and China (Northeast China Plain deciduous forests and Hengduan Mountains conifer forests; Fig. 4). … Forest fire C emissions showed opposing trends in the pyromes occupying the tropical deforestation zones, with a 96% decline (−26 Tg C $year^{-1}$) in forest fire C emissions in pyrome TropF2 outweighing 56% increases(+24TgC $year^{-1}$) in forest fire C emissions in pyrome TropF1 (Fig. 3).").

[332] Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, REV. GEOPHYS. 61: 1–81, 25–26 ("Tree mortality across the Russian boreal forest has increased over the late 20th and early 21st centuries (Allen et al., 2010). The same region has also seen a substantial intensification in fire occurrence, with the fire return interval falling from 101 years in the 19th century to 65 years in the 20th century for larch-dominant forest stands (Kharuk et al., 2008). Increased recurrence of wildfires is reducing the carbon stocks of affected boreal forest sites (Palviainen et al., 2020), altering soil and permafrost regimes (Gibson et al., 2018), changing dominant species compositions (Baltzer et al., 2021; Mack et al., 2021), and in some cases leading to post-fire "regeneration failure" (Burrell et al., 2021). Forest area burned has correspondingly increased across Siberia based on data from multiple sources (Soja et al., 2007). The extent of wildfires in boreal environments is widely anticipated to continue increasing in the future (Balshi et al., 2009; Kloster et al., 2012; Shuman et al., 2017; Wotton et al., 2017)…For example, one study predicts that the probability and intensity of Canadian boreal forest fires might more than double across large areas by 2080–2100 under an RCP8.5 scenario (Wotton et al., 2017), while another recent analysis modeled mean potential increases in burned area of 29%–35% for the Northwest Territories and 46%–55% for interior Alaska by 2050–2074 under RCP8.5, driven predominantly by more frequent occurrence of lightning (Veraverbeke et al., 2017).").

[333] Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, REV. GEOPHYS. 61: 1–81, 24 ("Higher temperatures have additionally been linked to acute outbreaks of insects leading to large-scale tree mortality events in Alaska, Canada, and Siberia (Boyd et al., 2021; Kharuk et al., 2020; Kurz et al., 2008; Sherriff et al., 2011; US Forest Service, 2019), sparking concern that similar pest invasions could occur more often in the future, infecting new tree species and expanding pest ranges northward (de la Giroday et al., 2012).").

[334] Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, REV. GEOPHYS. 61: 1–81, 26 ("The rapid pace of such observed and predicted patterns, which in some cases exceed older predictions, raises the possibility that future change and warming-induced feedbacks within the boreal biome may proceed non-linearly rather than linearly (Foster et al., 2019; Johnstone et al., 2010; Soja et al., 2007). An extensive survey of forest cover across the boreal environment has indicated that intermediate states of landscape tree cover are rare and potentially unstable, suggesting that forested areas may transition to systems with sparse tree cover more abruptly than previously thought (Scheffer, Hirota, et al., 2012). Shifts toward more prevalent fires potentially play a major role in driving a transition toward more deciduous tree cover (Johnstone et al., 2010).").

[335] Walker X. J., Baltzer J. L., Cumming S. G., Day N. J., Ebert C., Goetz S., Johnstone J. F., Potter S., Rogers B. M., Schuur E. A. G., Turetsky M. R., & Mack M. C. (2019) *Increasing wildfires threaten historic carbon sink of boreal forest soils*, NATURE 572(7770): 520–523, 522–523 ("Burn depth and C emissions were similar, regardless of legacy C combustion (Extended Data Table 3). These results suggest that legacy C combustion in young burned plots is due to its more shallow position in the organic soil, because the shorter time between consecutive fires limited organic-soil accumulation. …This demonstrates that relatively young legacy C combusted and that the amount of organic-soil C lost during the latest fire was higher than that accumulated since the previous fire but lower than the amount accumulated over preceding fire intervals. Taken together, our results suggest that an increase in fire frequency (that is, shortened interval between fires, resulting in more young burned forests) will be an important determinant of future legacy C loss. It follows that measuring the magnitude of C emissions alone is insufficient for assessing the long-term impacts of wildfire on the net carbon balance of boreal ecosystems … Similarly, legacy C emissions from increasing fire frequency in boreal forests, which take a century to re-sequester, represent a fundamental switch from a long-term carbon sink to a source … These changes will increase the proportion of young forests vulnerable to burning and increase both the loss of legacy C per unit area burned and the expanse of forests transitioning from net C uptake over consecutive fire intervals to net C loss. Accounting for fire frequency and associated legacy C loss is therefore important for assessing the effects of wildfire on the future boreal net ecosystem carbon balance and its impacts on the global C cycle and the climate.").

[336] Zhao B., Zhuang Q., Shurpali N., Köster K., Berninger F., & Pumpanen J. (2021) *North American boreal forests are a large carbon source due to wildfires from 1986 to 2016*, SCI. REP. 11(7723): 1-14, 1, 6 ("We observed that the region was a C source of 2.74 Pg C during the 31-year period. The observed C loss, 57.1 Tg C year^{-1}, was attributed to fire emissions, overwhelming the net ecosystem production (1.9 Tg C year^{-1}) in the region."; "The difference between total emissions with and without considering fires and the direct emission is presented in this study as a ratio (Supplementary Fig. S2d). When the ratio is larger than one, a fire results in a higher pro- portion of indirect emissions via RH. However, when the ratio is close to one, the fire even triggered a destruction of the standing vegetation and reduced post-fire RH. …However, for all severity classes, the ratio increased in the 25 years after the fire, suggesting that the ecosystem and vegetation were yet to recover to the pre-fire stage. As a result, plant productivity did not exceed the ecosystem respiration.").

[337] Sedano F. & Randerson J. T. (2014) *Multi-scale influence of vapor pressure deficit on fire ignition and spread in boreal forest ecosystems*, BIOGEOSCI. 11(14): 3739–3755, 3750 ("We found strong positive relationships between VPD and burned area at different temporal and spatial scales. This relationship was observed at a fine temporal resolution (daily VPD versus daily burned area) for individual fires, at a regional level within a single fire season, and across different years for the study domain as a whole. VPD also was implicated as an important climate regulator during multiple fire stages including, specifically, the probability that a lightning strike triggered ignition, during periods of initial fire spread, for daily burned area variations in larger fires, and the timing of fire extinction."). *See also* Clarke H., Nolan R. H., De Dios V. R., Bradstock R., Griebel A., Khanal S., & Boer M. M. (2022) *Forest fire threatens global carbon sinks and population centres under rising atmospheric water demand*, NAT. COMMUN. 13: 1–10, 3 ("We found that for many forested regions, and for the majority of global burned area in forests, the probability of fire occurrence can be accurately predicted on the basis of exceedance of thresholds in daily maximum VPD. We also found that the value of these thresholds varied predictably across major forest types, being highest in tropical and subtropical forests and lowest in temperate and boreal forests."). *See also* Jones M. W., Veraverbeke S., Andela N., Doerr S. H., Kolden C., Mataveli G., Pettinari M. L., Le Quéré C., Rosan T. M., Van Der Werf G. R., Van Wees D., & Abatzoglou J. T. (2024) *Global rise in forest fire emissions linked to climate change in the extratropics*, SCIENCE 386(6719): 1–12, 7 ("The increases in forest BA and fire C emissions in pyrome ExTropF2 align with changes in the variables that control temporal variability in forest BA. During 2001 to 2023, the annual number of extreme fire weather days increased by 5 days per year on average across the ecoregions of the pyrome (Fig. 4, fig. S14, and table S2). The average soil moisture content during the fire season decreased by around 3% on average, in contrast to other extratropical pyromes where soil moisture either increased or remained level (Fig. 4, fig. S15, and table S2). Mean NDVI [growing season vegetation productivity] during the growing season also increased at a rate comparable to the other extratropical pyromes (Fig. 4, fig. S16, and table S2). These trends were also widespread and consistent. For example, over half of the ecoregions in pyrome ExTropF2 synchronously experienced an increase in extreme fire weather days, increased NDVI, and reduced soil moisture, with over one-quarter of ecoregions showing significant

changes for all three variables. This evidence suggests that the trends in forest BA and fire C emissions in pyrome ExTropF2 were driven by changes in the climate of the fire season, which led to reduced fuel moisture, combined with changes in the climate of the growing season, which in turn led to increased vegetation growth and fuel production.").

[338] Qiao L., Zuo Z., Zhang R., Piao S., Xiao D., & Zhang K. (2023) *Soil moisture–atmosphere coupling accelerates global warming*, NAT. COMMUN. 14(4908): 1–10, 3 ("Under the very high-emission scenario, progressively drying soil column leads to an acceleration of the decline in evapotranspiration (Fig. 4b, d), with the result of increased positive radiative budgets and thereby the acceleration of the amplified-warming, particularly over NA and EUR…The enhanced sensitivity of evapotranspiration to soil drying leads to the increase of SA-induced non-linear warming under very high GHG emission background. The non-linear increase of SA-induced warming, combined with the GHGwarming, will make global warming to act like a snowball...").

[339] Qiao L., Zuo Z., Zhang R., Piao S., Xiao D., & Zhang K. (2023) *Soil moisture–atmosphere coupling accelerates global warming*, NAT. COMMUN. 14(4908): 1–10, 2–3 ("Clearly, the uptrend of SA-induced warming associated with very high greenhouse gases emission would accelerate the speed of global warming, and the magnitude of acceleration would increase with time. Therefore, we posit that, unless we take early action to reduce emission, SA- and GHG-induced warming would become closely coupled, resulting in a positive feedback that may hasten the approach of distinct climate range. Should the most stringent emission pathway be adopted, our results suggest SA-induced warming will weaken significantly (Fig. 2a).").

[340] Qiao L., Zuo Z., Zhang R., Piao S., Xiao D., & Zhang K. (2023) *Soil moisture–atmosphere coupling accelerates global warming*, NAT. COMMUN. 14(4908): 1–10, 5–6 ("Output from CMIP6's LS3MIP and ScenarioMIP experiments projects that very high GHG emission will result in soil drying and reduced evapotranspiration, thereby forcing more heat into the atmosphere via enhanced downward shortwave radiation and sensible heat flux. Such SA conditions will serve to further amplify the GHG-driven warming. Under the worst (highest) emission scenario, the amplification due to SA is projected to increase over time owing to the uptrend evapotranspiration rate associated with drying soil, which follows an accelerating amplified-warming. Such acceleration in SA-warming will make extreme high-temperature events both more frequent and more severe, particularly over North America and Europe. The implication of these findings suggests that mitigation efforts corresponding to acceleration of SA-driven warming must be implemented at an early stage to minimize the risk of climate shock."). *See also* Clarke H., Nolan R. H., De Dios V. R., Bradstock R., Griebel A., Khanal S., & Boer M. M. (2022) *Forest fire threatens global carbon sinks and population centres under rising atmospheric water demand*, NAT. COMMUN. 13(7161): 1–10, 3 ("Unmitigated climate change is projected to lead to widespread increases in the frequency of days exceeding VPD thresholds associated with elevated probability of fire. Under a high emissions scenario (RCP8.5), by 2026–2045 all models projected at least 45 additional days per year above the VPD threshold in parts of tropical South America, with two out of three models also projecting increases of this magnitude in North America, east Africa and large parts of Europe (Supplementary Fig. 4).").

[341] Dahl K. A., Abatzoglou J. T., Phillips C. A., Ortiz-Partida J. P., Licker R., Merner L. D., & Ekwurzel B. (2023) *Quantifying the contribution of major carbon producers to increases in vapor pressure deficit and burned area in western US and southwestern Canadian forests*, ENVIRON. RES. LETT. 18(6): 1–11, 8 ("Here, we find that the emissions of the world's largest 88 carbon producers contributed 48% of the increase in VPD since 1901 and 37% of the cumulative BA in the forested lands of western US and southwestern Canada since 1986, establishing the regional impacts of climate change in relation to corporate emitters and underscoring the responsibility these companies bear for the impacts of climate change.").

[342] Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, REV. GEOPHYS. 61: 1–81, 26 ("Yet while boreal forest productivity and tree cover are on the decline at the southern edge of the boreal zone and within interior regions, 30-year data sets of satellite and observational evidence also point toward ongoing expansion of boreal forests northwards into area previously occupied by tundra thanks to higher temperatures (Figure 9) (Beck, Juday, et al., 2011; Ju & Masek, 2016; Pastick et al., 2019; Pearson et al., 2013). Since 1960, the growing season across the boreal zone has lengthened by 3 days/decade (Euskirchen et al., 2006). Expansion of trees into the

tundra biome has implications for regional and global climate, as the albedo of forests is lower than that of tundra, leading to warmer winter conditions with greater tree cover (Bonan et al., 1992).").

[343] Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, REV. GEOPHYS. 61: 1–81, 28 ("Overall, the climatic impact of worldwide changes to the boreal biome under expected future emissions remains challenging to assess. Reductions in boreal forest area in southern and upland boreal regions combined with fire regime changes and the predicted northward treeline expansion in response to higher temperatures produce multiple competing, complex climate impacts (Beck, Goetz, et al., 2011; Foster et al., 2019; Ju & Masek, 2016; Pastick et al., 2019; Pearson et al., 2013). Calculations of changes to carbon stocks, regional albedo, carbon sinks, and the timescales involved even at local or regional scales remain imprecise and depend upon multiple complex processes and feedbacks (Foster et al., 2019; Shuman et al., 2015). Ultimately, current research cannot eliminate the possibility that changes across the boreal zone due to a warming climate could act as a net positive climate feedback, thanks to the potential for permafrost thaw and wildfires to liberate the soil carbon that makes up the majority of stored carbon across this ecosystem. Consequently, boreal forest dieback and shifts represent one of the more potentially immediate and significant climate system tipping elements (Table 7).").

[344] Lovejoy T. E. & Nobre C. (2018) *Amazon's Tipping Point*, SCI. ADV. 4(2): eaat2340, 1 ("We believe that negative synergies between deforestation, climate change, and widespread use of fire indicate a tipping point for the Amazon system to flip to nonforest ecosystems in eastern, southern and central Amazonia at 20–25% deforestation."). *See also* Hoegh-Guldberg O., *et al.* (2018) *Chapter 3: Impacts of 1.5 ºC of Global Warming on Natural and Human Systems*, *in* GLOBAL WARMING OF 1.5 °C, *Special Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 3-263 ("Global warming of 3°C is projected to reduce the extent of tropical rainforest in Central America, with biomass being reduced by about 40%, which can lead to a large replacement of rainforest by savanna and grassland (Lyra et al., 2017). Overall, modelling studies (Huntingford et al., 2013; Nobre et al., 2016) and observational constraints (Cox et al., 2013) suggest that pronounced rainforest dieback may only be triggered at 3°C–4°C (*medium confidence*), although pronounced biomass losses may occur at 1.5°C– 2°C of global warming.").

[345] Taylor L. (5 September 2022) *The Amazon rainforest has already reached a crucial tipping point,* NEW SCIENTIST ("Marlene Quintanilla at the Amazon Geo-Referenced Socio-Environmental Information Network (RAISG) and her colleagues, working in partnership with various groups, including the Coordinator of Indigenous Organizations of the Amazon River Basin, used forest coverage data to map how much of the Amazon was lost between 1985 and 2020 and also looked at forest density, rainfall patterns and carbon storage. …The report finds that 33 per cent of the Amazon remains pristine and 41 per cent of areas have low degradation and could restore themselves. But 26 per cent of areas have been found to have gone too far to restore themselves: 20 per cent is lost entirely and 6 per cent is highly degraded and would need human support to be restored."). *See also* Lenton T. M., Rockstrom J., Gaffney O., Rahmstorf S., Richardson K., Steffen W., & Schellnhuber H. J. (2019) *Climate tipping points—too risky to bet against*, Comment, NATURE 575: 592–595, 593 ("Estimates of where an Amazon tipping point could lie range from 40% deforestation to just 30% forest-cover loss. About 17% has been lost since 1970. The rate of deforestation varies with changes in policy. Finding the tipping point requires models that include deforestation and climate change as interacting drivers, and that incorporate fire and climate feedbacks as interacting tipping mechanisms across scales."); *and* Armstrong McKay D. I. & Loriani S. (eds.) (2023) *Section 1: Earth systems tipping points*, in GLOBAL TIPPING POINTS REPORT 2023, Lenton T. M., et al. (eds.), 41 ("Among tropical forests, the Amazon forest has most evidence for potential tipping points. Analysis based on early warning signals (see Chapter 1.6) indicates that over 75 per cent of the Amazon has lost resilience since the early 2000s (Boulton et al., 2022). This decline is focused mostly closer to human disturbance, as well as in the drier south and east previously identified as 'bistable' (i.e. with two possible alternative states) due to the forest-rainfall feedback and thus is more vulnerable to tipping (Staal et al., 2020). While the Amazon has acted as a carbon sink due to CO_2 fertilisation, in mature forest this sink peaked and started declining in the 1990s (Hubau et al., 2020) and when including degraded forest (also predominantly in the drier south and east) the Amazon as a whole is now a carbon source (Gatti et al., 2021).").

[346] Marsden L., Ryan-Collins J., Abrams J. F., & Lenton T. M. (2024) ECOSYSTEM TIPPING POINTS: UNDERSTANDING RISKS TO THE ECONOMY AND FINANCIAL SYSTEM, UCL Institute for Innovation and Public Purpose, 8 ("While all

tipping points pose globally systemic risks, those in the biosphere – ecosystem tipping points (ETPs) – require specific intervention. In addition to the presence of multiple drivers that make their behaviour particularly uncertain, ecosystems can collapse much faster than cryosphere and ocean sub-systems."); 16 ("Tropical ecosystems with tipping points, such as the Amazon rainforest, tropical peatlands and mangroves, currently sequester globally significant volumes of carbon in the order of 220 gigatonnes. This is around 20 years of global CO2e emissions based on 2022 rates, that could be quickly destabilised by tipping events, on timescales of months to decades.[1,26,61] Emissions from fires, in particular, can occur very rapidly the 2015 peatland fires in Indonesia released enough carbon to exceed the annual emissions of the US economy in just five months.[62]").

[347] Flores B. M., et al. (2024) *Critical transitions in the Amazon forest system*, NATURE 626(7999): 555–564, 558 ("[W]e combined spatial information on warming and drying trends, repeated extreme drought events, together with road networks, as proxy for future deforestation and degradation. We also included protected areas and Indigenous territories as areas with high forest governance, where deforestation and fire regimes are among the lowest within the Amazon (Fig. 1e). This simple additive approach does not consider synergies between compounding disturbances that could trigger unexpected ecosystem transitions…We found that 10% of the Amazon forest biome has a relatively high transition potential (more than 2 disturbance types; Fig. 1f), including bistable forests that could transition into a low tree cover state near savannas of Guyana, Venezuela, Colombia and Peru, as well as stable forests that could transition into alternative compositional states within the central Amazon, such as along the BR319 and Trans-Amazonian highways…Moreover, 47% of the biome has a moderate transition potential (more than 1 disturbance type; Fig. 1f), including relatively remote parts of the central Amazon where warming trends and repeated extreme drought events overlap (Fig. 1a,c)."). *See also* Douville H., et al. (2021) *Chapter 8: Water Cycle Changes*, in CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Masson-Delmotte V., et al. (eds.), 1149 ("Both deforestation and drying are projected to increase by 2100, resulting in a worst-case scenario of up to a 50% loss in forest cover by 2050 (Soares-Filho et al., 2006; Boisier et al., 2015; Steege et 50 al., 2015; Gomes et al., 2019).").

[348] Wang-Erlandsson L., *et al.* (2022) *A planetary boundary for green water*, NAT. REV. EARTH ENVIRON. 3: 380–392, 380 ("Green water — terrestrial precipitation, evaporation and soil moisture — is fundamental to Earth system dynamics and is now extensively perturbed by human pressures at continental to planetary scales. However, green water lacks explicit consideration in the existing planetary boundaries framework that demarcates a global safe operating space for humanity. In this Perspective, we propose a green water planetary boundary and estimate its current status. The green water planetary boundary can be represented by the percentage of ice-free land area on which root-zone soil moisture deviates from Holocene variability for any month of the year. Provisional estimates of departures from Holocene-like conditions, alongside evidence of widespread deterioration in Earth system functioning, indicate that the green water planetary boundary is already transgressed. Moving forward, research needs to address and account for the role of root-zone soil moisture for Earth system resilience in view of ecohydrological, hydroclimatic and sociohydrological interactions."), *discussed in* Stockhom Resilience Center (26 April 2022) *Freshwater boundary exceeds safe limits* ("Now researchers have explored the water boundary in more detail. The authors argue that previous assessments did not sufficiently capture the role of green water and particularly soil moisture for ensuring the resilience of the biosphere, for securing land carbon sinks, and for regulating atmospheric circulation. "The Amazon rainforest depends on soil moisture for its survival. But there is evidence that parts of the Amazon are drying out. The forest is losing soil moisture as a result of climate change and deforestation," says Arne Tobian, second author and PhD candidate at the Stockholm Resilience Centre and Potsdam Institute for Climate Impact Research. "These changes are potentially pushing the Amazon closer to a tipping point where large parts could switch from rainforest to savannah-like states," he adds.").

[349] Feron S., Cordero R. R., Damiani A., MacDonell S., Pizarro J., Goubanova K., Valenzuela R., Wang C., Rester L., & Beaulieu A. (2024) *South America is becoming warmer, drier, and more flammable*, COMMUN. EARTH ENVIRON. 5(1): 1–10, 3 ("Climate-driven warm temperatures and droughts are contributing to an enhanced fire risk (i.e., flammable conditions). The rise in extreme fire weather conditions has been particularly steep in the northern Amazon, Maracaibo, and Gran Chaco regions (Fig. 2c). While flammable conditions were present generally less than 40 days per year over the period 1971–2000 (Fig. S7a), these conditions arose up to 120 days per year in the northern Amazon and Maracaibo regions over the last decade (Fig. S7b).").

[350] Boulton C. A., Lenton T. M., & Boers N. (2022) *Pronounced loss of Amazon rainforest resilience since the early 2000s*, NAT. CLIM. CHANG. 12(3): 271–78, 277 ("Other factors, including rising atmospheric temperatures in response to anthropogenic greenhouse gas emissions, may additionally have negative effects on Amazon resilience (and are contributing to the warming of northern tropical Atlantic SSTs; Fig. 6a). Furthermore, the rapid change in climate is triggering ecological changes but ecosystems are having difficulties in keeping pace. In particular, the replacement of drought-sensitive tree species by drought-resistant ones is happening slower than changes in (hydro)meteorological conditions50, potentially reducing forest resilience further. In summary, we have revealed empirical evidence that the Amazon rainforest has been losing resilience since the early 2000s, risking dieback with profound implications for biodiversity, carbon storage and climate change at a global scale. We further provided empirical evidence suggesting that overall drier conditions, culminating in three severe drought events, combined with pronounced increases in human land-use activity in the Amazon, probably played a crucial role in the observed resilience loss. The amplified loss of Amazon resilience in areas closer to human land use suggests that reducing deforestation will not just protect the parts of the forest that are directly threatened but also benefit Amazon rainforest resilience over much larger spatial scales.").

[351] Lenton T. M., Held H., Kriegler E., Hall J. W., Lucht W., Rahmstorf S., & Schellnhuber H. J. (2008) *Tipping elements in the Earth's climate system*, PROC. NAT'L. ACAD. SCI. 105(6): 1786–1793, 1790 ("A large fraction of precipitation in the Amazon basin is recycled, and, therefore, simulations of Amazon deforestation typically generate 20–30% reductions in precipitation (78), lengthening of the dry season, and increases in summer temperatures (79) that would make it difficult for the forest to reestablish, and suggest the system may exhibit bistability."). *See also* Staal A., Fetzer I., Wang-Erlandsson L., Bosmans J. H. C., Dekker S. C., van Nes E. H., Rockström J., & Tuinenburg O. A. (2020) *Hysteresis of tropical forests in the 21st century*, NAT. COMMUN. 11(4978): 1–8, 5 ("Whether the Amazon in particular is an important global 'tipping element' in the Earth system is a question of great scientific and societal interest[36,37]. Despite our incomplete understanding of Amazon tipping, it is generally considered to be true that the forest's role in the hydrological cycle is so large that deforestation and/or climate change may trigger a tipping point [2,36–38]. More recently, the possibility of fire-induced tipping has also been suggested [5,6]. Although fire occurs at a local scale, a considerable portion of the Amazon would be susceptible to this kind of tipping; by accounting for the feed-backs at both local and regional scales, it becomes more likely that the Amazon is a tipping element. Although under the current climate a majority of the Amazon forest still appears resilient to disturbance (also see ref. 39), we show that this resilience may deteriorate as a result of redistributions of rainfall due to global climate change.").

[352] Gatti L. V., *et al.* (2021) *Amazonia as a carbon source linked to deforestation and climate change*, NATURE 595(7867): 388–393, 388 ("Southeastern Amazonia, in particular, acts as a net carbon source (total carbon flux minus fire emissions) to the atmosphere. Over the past 40 years, eastern Amazonia has been subjected to more deforestation, warming and moisture stress than the western part, especially during the dry season… the intensification of the dry season and an increase in deforestation seem to promote ecosystem stress, increase in fire occurrence, and higher carbon emissions in the eastern Amazon. This is in line with recent studies that indicate an increase in tree mortality and a reduction in photosynthesis as a result of climatic changes across Amazonia."). *See also* Brienen R. J. W., *et al.* (2015) *Long-term decline of the Amazon carbon sink*, NATURE 519(7543): 344–348, 344 ("While this analysis confirms that Amazon forests have acted as a long-term net biomass sink, we find a long-term decreasing trend of carbon accumulation. Rates of net increase in above-ground biomass declined by one-third during the past decade compared to the 1990s. This is a consequence of growth rate increases levelling off recently, while biomass mortality persistently increased throughout, leading to a shortening of carbon residence times.").

[353] Clarke B., Barnes C., Rodrigues R., Zachariah M., Stewart S., Raju E., Baumgart N., Heinrich D., Libonati R., Santos D., Albuquerque R., Muniz Alves L., & Otto F. (2024) *Climate change, not El Niño, main driver of exceptional drought in highly vulnerable Amazon River Basin*, World Weather Attribution, 3–4 ("Since June 2023, the Amazon River Basin (ARB) has received significantly below average rainfall. Initially, the northern half of the basin was most affected by this, but from September the entire basin has experienced a significant moisture deficit. … As of January 2024, large parts of the ARB are in a state of exceptional meteorological, agricultural and ecological drought (WMO, 2016). … The drought has caused the lowest water levels in 120 years, when measurements began, in many of the tributaries in the Amazon River (nature, 2023)."); 4–5 ("The ARB is extremely large, making up more than a third of

the South American continent by land area, stretching from the high Andes in Peru and Colombia down to low-lying coastal regions of eastern Brazil, and is largely a tropical climate. Rainforest covers approximately 83% of the basin, and spatial variability of rainfall over the region is partly determined by feedbacks between the land surface and atmosphere (Paredes-Trejo et al., 2021).”); 34 (“The 2023 Amazon drought is frequently cited as the most extreme on the historical record.”).

[354] Drollette D. (12 March 2025) *Carlos Nobre on tipping points in the Amazon rainforest*, BULLETIN OF THE ATOMIC SCIENTISTS (“[T]he Amazon had record-breaking drought, and record-breaking fires—which also put the Amazon at its lowest river level in history. All these issues came together, to make 2023 and 2024 closest to the tipping point ever. … [W]here historically the dry season lasted three to four months, now it’s already 4 to 5 months, which is dangerously close. As soon as it reaches six months, that’s the point at which you hit the climate envelope.”) *See also* Clarke B., Barnes C., Rodrigues R., Zachariah M., Stewart S., Raju E., Baumgart N., Heinrich D., Libonati R., Santos D., Albuquerque R., Muniz Alves L., & Otto F. (2024) *Climate change, not El Niño, main driver of exceptional drought in highly vulnerable Amazon River Basin*, World Weather Attribution, 4–5 (“Finally, while the rate of deforestation has decreased in the past year, multiple years of heightened deforestation previously have resulted in a less resilient and drier land surface (Rodrigues, 2023). Moreover, droughts in the northwestern Amazon such as this can be especially devastating to the forest and potentially accelerate a tipping point because the forest there is less resilient to rainfall variability than that in the eastern Amazon, which experiences more variability (Ciemer et al., 2019; Hirota et al., 2021).”); *and* Armstrong McKay D. I. & Loriani S. (eds.) (2023) *Section 1: Earth systems tipping points*, in GLOBAL TIPPING POINTS REPORT 2023, Lenton T. M., *et al.* (eds.), 41 (“Recent CMIP6 models indicate that localised shifts in peripheral parts of the Amazon forest system are more likely than a large-scale tipping event (IPCC AR6 WG1 Ch5, 2021; Parry et al., 2022). However, the latter cannot be ruled out (Hirota et al., 2021) because several compounding and possibly synergistic disturbances (e.g. combining an extreme hot drought with forest fires) may play a role in reducing forest resilience, with greater resilience loss closer to human activities (Boulton et al., 2022). Such synergies are generally not considered in Earth system models (Willcock et al., 2023).”); 113 (“For example, if the system is perturbed by something like an extreme weather event (e.g. a drought in the Amazon rainforest) such that it causes tipping by pushing the system past the ability for restoring feedbacks to return the system back to the previous state, CSD will not occur.”).

[355] Goldstein A., Noon M. L., Ledezma J. C., Roehrdanz P. R., Raghav S., McGreevey M., Stone C., Shrestha S., Golden Kroner R., Hole D., & Turner W. (2021) IRRECOVERABLE CARBON: THE PLACES WE MUST PROTECT TO AVERT CLIMATE CATASTROPHE, Conservation International, 7 (“‘Irrecoverable carbon’ refers to the vast stores of carbon in nature that are vulnerable to release from human activity and, if lost, could not be restored by 2050 — when the world must reach net-zero emissions to avoid the worst impacts of climate change … There are high concentrations of irrecoverable carbon in the Amazon (31.5 Gt), the Congo Basin (8.1 Gt), and New Guinea (7.3 Gt). Other important irrecoverable carbon reserves are located in the Pacific Northwest of North America, the Valdivian forests of Chile, the mangroves and swamp forests of Guyana, the peatlands of Northern Scotland, Niger Delta’s mangroves, Cambodia’s Tonle Sap Lake, the Scandinavian and Siberian boreal forests, and the eucalyptus forest of Southeast Australia, among others.”). *See also* Goldstein A., *et al.* (2020) *Protecting irrecoverable carbon in Earth’s ecosystems*, NAT. CLIM. CHANGE 10(4): 287–295; *and* Noon M. L., Goldstein A., Ledezma J. C., Roehrdanz P. R., Cook-Patton S. C., Spawn-Lee S. A., Wright T. M., Gonzalez-Roglich M., Hole D. G., Rockström J., & Turner W. R. (2021) *Mapping the irrecoverable carbon in Earth’s ecosystems*, NAT. SUSTAIN. 5: 37–46.

[356] Gauci V., Pangala S. R., Shenkin A., Barba J., Bastviken D., Figueiredo V., Gomez C., Enrich-Prast A., Sayer E., Stauffer T., Welch B., Elias D., McNamara N., Allen M., & Malhi Y. (2024) *Global atmospheric methane uptake by upland tree woody surfaces*, NATURE 631(8022): 796–800, 796 (“Stable carbon isotope measurement of methane in woody surface chamber air and process-level investigations on extracted wood cores are consistent with methanotrophy, suggesting a microbially mediated drawdown of methane on and in tree woody surfaces and tissues. By applying terrestrial laser scanning-derived allometry to quantify global forest tree woody surface area, a preliminary first estimate suggests that trees may contribute 24.6–49.9 Tg of atmospheric methane uptake globally. Our findings indicate that the climate benefits of tropical and temperate forest protection and reforestation may be greater than previously assumed. … At the global scale, the atmospheric CH4 sink terms (for example, hydroxyl (OH) radicals and ultraviolet-associated processes) dominate CH4 losses[.])”.

[357] Gauci V., Pangala S. R., Shenkin A., Barba J., Bastviken D., Figueiredo V., Gomez C., Enrich-Prast A., Sayer E., Stauffer T., Welch B., Elias D., McNamara N., Allen M., & Malhi Y. (2024) *Global atmospheric methane uptake by upland tree woody surfaces*, NATURE 631(8022): 796–800, 799–800 ("We consider the CH_4 sink consequences of removing trees to be small relative to total biomass C loss; however, the impact of reforestation may be more significant. Despite the lower biomass of secondary forests, their large numbers of small trees mean that they often have high woody surface area, similar to or higher than that of old growth forests[28,29]. We estimate an extra greenhouse gas mitigation value from CH_4 uptake as equivalent to 0.131 and 0.586 Mg of C ha^{-1} yr^{-1} in temperate and tropical forests, respectively, corresponding to a 7% and 12% extra climate benefit of new trees in these respective biomes. This suggests a possible global extra climate benefit, through the enlarged tree CH_4 sink, equivalent to up to 0.3 Pg of C yr^{-1} or 1.1 Pg of CO_2-we yr^{-1}. This is equivalent to a 10% extra mitigation potential over benefits already estimated for expansion of temperate and tropical forests[30,31].").

[358] Girardin C. A. J., Jenkins S., Seddon N., Allen M., Lewis S. L., Wheeler C. E., Griscom B. W., & Malhi Y. (2021) *Nature-based solutions can help cool the planet — if we act now*, Comment, NATURE 593: 191–194, 192 ("A subset of nature-based solutions can be used specifically to limit warming. These 'natural climate solutions' aim to reduce atmospheric greenhouse-gas concentrations in three ways. One is to avoid emissions by protecting ecosystems and thus reducing carbon release; this includes efforts to limit deforestation. Another is to restore ecosystems, such as wetlands, so that they sequester carbon. The third is to improve land management — for timber, crops and grazing — to reduce emissions of carbon, methane and nitrous oxide, as well as to sequester carbon (see 'Three steps to natural cooling')."). *See also* Moustakis Y., Nützel T., Wey H.-W., Bao W., & Pongratz J. (2024) *Temperature overshoot responses to ambitious forestation in an Earth System Model*, NAT. COMMUN. 15(1): 1–18, 4 ("Comparing the REF [reference scenario] and AR [afforestation/reforestation] simulations suggests that the isolated effect of AR on average global temperature yields peak temperature reduced by ~0.08C, overshoot duration by ~13 years, and end-ofcentury temperature by ~0.2C. The impact of AR on global temperature emerges already in ~2052 ± 2 years, when the temperature difference with REF starts becoming statistically significant (Fig. 4a). At that point, AR has reached 495 Mha, atmospheric carbon is lower by ~110 GtCO2 (30 PgC, 14 ppm), and oceanic carbon by ~22 GtCO2 (6 PgC), due to a total increase of ~132 GtCO2 (36PgC)in the land carbon sink (Fig. 4b)."); 10 ("The mitigation potential demonstrated here constitutes ambitious AR as a useful complementary short- and long-term mitigation tool for climate action even under a scenario with strongly reduced emissions, where fertilization of vegetation by CO2 is weaker. However, the scale of mitigation achievable by such high-ambition AR scenarios—with 0.08C and 0.2C decrease of global mean peak and end-of-century temperature respectively—clearly shows that AR does not alleviate the need for high ambitions in emission reduction[52]. Importantly, even though a normative judgment on the desirability of ambitious AR is not made here, the results demonstrate the possible socioeconomic tradeoffs associated with it, as well as the significant barriers to implementation and possible threats to permanence that exist.").

[359] Moomaw W. R., Masino S. A., & Faison E. K. (2019) *Intact Forests in the United States: Proforestation Mitigates Climate Change and Serves the Greatest Good*, FRONT. FOR. GLOB. CHANGE 2(27): 1–10, 1 ("The recent *1.5 Degree Warming Report* by the Intergovernmental Panel on Climate Change identifies *reforestation* and *afforestation* as important strategies to increase negative emissions, but they face significant challenges: afforestation requires an enormous amount of additional land, and neither strategy can remove sufficient carbon by growing young trees during the critical next decade(s). In contrast, growing existing forests intact to their ecological potential—termed *proforestation*—is a more effective, immediate, and low-cost approach that could be mobilized across suitable forests of all types. Proforestation serves the greatest public good by maximizing co-benefits such as nature-based biological carbon sequestration and unparalleled ecosystem services such as biodiversity enhancement, water and air quality, flood and erosion control, public health benefits, low impact recreation, and scenic beauty."). *See also* Lewis S. L., Wheeler C. E., Mitchard E. T. A., & Koch A. (2019) *Restoring natural forests is the best way to remove atmospheric carbon*, NATURE 568(7750): 25–28, 28 ("[C]ountries should increase the proportion of land that is being regenerated to natural forest. Each additional 8.6 Mha sequesters another 1 Pg C by 2100. That is an area roughly the size of the island of Ireland, or the state of South Carolina. Second, prioritize natural regeneration in the humid tropics, such as Amazonia, Borneo or the Congo Basin, which all support very high biomass forest compared with drier regions. ... Target degraded forests and partly wooded areas for natural regeneration[.]").

[360] United Nations Environment Programme & GRID-Arendal (2017) SMOKE ON WATER: COUNTERING GLOBAL THREATS FROM PEATLANDS LOSS AND DEGRADATION, A RAPID RESPONSE ASSESSMENT, Crump J. (ed.), 9 ("Current greenhouse gas emissions from drained or burning peatlands are estimated to be up to five percent of all emissions caused by human activity – in the range of two billion tonnes of CO_2 per year. If the world has any hope of keeping the global average temperature increase under two degrees Celsius then urgent action must be taken to keep the carbon locked in peatlands where it is – wet, and in the ground to prevent an increase in emissions. Furthermore, already drained peatlands must be rewetted to halt their ongoing significant emissions. However, this is not as simple as it seems. Knowing the location of peatlands continues to be a challenge."). *See also* Humpenöder F., Karstens K., Lotze-Campen H., Leifeld J., Menichetti L., Barthelmes A., & Popp A. (2020) *Peatland Protection and Restoration are Key for Climate Change Mitigation*, ENVIRON. RES. LETT. 15(10): 1–12, 10 ("However, in line with other studies (Leifeld et al 2019), our results indicate that it is possible to reconcile land use and GHG emissions in mitigation pathways through a peatland protection and restoration policy (RCP2.6 + PeatRestor). Our results suggest that the land system would turn into a global net carbon sink by 2100, as projected by current mitigation pathways, if about 60% of present-day degraded peatlands, mainly in the tropical and boreal climate zone, would be rewetted in the coming decades, next to the protection of intact peatlands. Therefore, peatland protection and restoration are key for climate change mitigation. At the same time, our results indicate that the implementation costs of peatland protection and restoration measures are low, and that there are almost no impacts on regional food security.").

[361] Intergovernmental Panel on Climate Change (2019) *Summary for Policymakers*, *in* THE OCEAN AND CRYOSPHERE IN A CHANGING CLIMATE, *Special Report of the Intergovernmental Panel on Climate Change*, Pörtner H.-O., *et al.* (eds.), SPM-30 ("Restoration of vegetated coastal ecosystems, such as mangroves, tidal marshes and seagrass meadows (coastal 'blue carbon' ecosystems), could provide climate change mitigation through increased carbon uptake and storage of around 0.5% of current global emissions annually (*medium confidence*). Improved protection and management can reduce carbon emissions from these ecosystems.").

[362] Booth M. S. (2018) *Not Carbon Neutral: Assessing the Net Emissions Impact of Residues Burned for Bioenergy*, ENVIRON. RES. LETT. 13(3): 1–10, 8 ("For bioenergy to offer genuine climate mitigation, it is essential to move beyond the assumption of instantaneous carbon neutrality. The [net emissions impact (NEI)] approach provides a simple means to estimate net bioenergy emissions over time, albeit one that tends to underestimate actual impacts. The model finds that for plants burning locally sourced wood residues, from 41% (extremely rapid decomposition) to 95% (very slow decomposition) of cumulative direct emissions should be counted as contributing to atmospheric carbon loading by year 10. Even by year 50 and beyond, the model shows that net emissions are a significant proportion of direct emissions for many fuels."). *See also* Sterman J. D., Siegel L., & Rooney-Varga J. N. (2018) *Does Replacing Coal with Wood Lower* CO_2 *Emissions? Dynamic Lifecycle Analysis of Wood Bioenergy*, ENVIRON. RES. LETT. 13(015007): 1–10, 6 ("Scenario 2 shows the realistic case with the combustion efficiency and supply chain emissions estimated for wood pellets (supplementary table S5), again assuming 25% of the biomass is harvested by thinning. Because production and combustion of wood generate more CO_2 than coal, the first impact of bioenergy use is an increase in atmospheric CO_2. Regrowth gradually transfers C from the atmosphere to biomass and soil C stocks, leading to a carbon debt payback time of 52 years; after 100 years CO_2 remains 62% above the zero C case."); *and* Bloomer L., Sun X., Dreyfus G., Ferris T., Zaelke D., & Schiff C. (2022) *A Call to Stop Burning Trees in the Name of Climate Mitigation*, VT. J. ENVTL. LAW 23: 94–123.

[363] UN Climate Change Conference (2 November 2021) *Glasgow Leaders' Declaration on Forests and Land Use* ("We therefore commit to working collectively to halt and reverse forest loss and land degradation by 2030 while delivering sustainable development and promoting an inclusive rural transformation.").

[364] Chandrasekhar A., Dunne D., Dwyer O., Quiroz Y., & Viglione G. (15 December 2023) *COP28: Key outcomes for food, forests, land and nature at the UN climate talks in Dubai*, CARBON BRIEF ("The global stocktake "emphasises" that halting and reversing deforestation and forest degradation by 2030 will be key to meet the goals of the Paris Agreement – the first time such a pledge has garnered formal recognition under the UN Framework Convention on Climate Change (UNFCCC).").

[365] Chandrasekhar A., Dunne D., Dwyer O., Quiroz Y., & Viglione G. (15 December 2023) *COP28: Key outcomes for food, forests, land and nature at the UN climate talks in Dubai*, CARBON BRIEF ("Brazil, which will host COP30 as the "tropical forests COP" in 2025, turned heads by announcing a new "tropical forests forever" fund proposal on 1 December."). Paraguassa L. (1 December 2023) *Brazil proposes global forest conservation fund at COP28*, REUTERS ("Brazil on Friday unveiled a proposal at the COP28 climate summit to set up a global fund to finance forest conservation that it hopes can raise $250 billion from sovereign wealth funds and other investors, including the oil industry. The proposal, presented at a panel during the meeting in Dubai, provides for funding to 80 countries that have tropical forests to help maintain their trees, with annual payments based on the hectares conserved or restored.").

[366] Forest Declaration Dashboard (*last visited* 18 February 2025) *Tracking progress towards 2030 goals to protect and restore forests and land*.

[367] Dooley K., *et al.* (2022) THE LAND GAP REPORT 2022, 21 ("While many governments include direct land areas in climate pledges, some make obscure assumptions or unquantifiable statements regarding the scale of land-based removals. Therefore, governments' climate pledges must present more clarity about the amount of land and land-use change planned to meet climate objectives. There is also a need for greater clarity about government pledges across United Nations conventions to avoid overlapping claims. Research shows that worldwide, governments (of at least 115 countries) have committed a total of close to 1 billion ha for land restoration (van der Esch et al., 2022). This is close to the land area for carbon removals that we found committed in climate pledges, but the restoration pledges in van der Esch et al., 2022 are found under a wider range of United Nations conventions (including the United Nations Convention to Combat Desertification (UNCCD) and the Convention on Biological Diversity (CBD) and the Bonn Challenge). It is not clear if these various pledges concern similar, overlapping or different areas of land. Again, more clarity is needed.").

[368] Dooley K., *et al.* (2022) THE LAND GAP REPORT 2022, 8 ("We find that almost 1.2 billion hectares (ha) of land – close to the extent of current global cropland – are required to meet these pledges. This finding shows that countries' climate pledges rely on unrealistic amounts of land-based carbon removal, which cannot be achieved without significant negative impacts on livelihoods, land rights, food production and ecosystems. For example, over half of this area (633 million ha) requires a land-use change to achieve the projected carbon removal, with the potential to displace food production including sustainable livelihoods for many smallholder farmers. Slightly less than half (551 million ha) would restore degraded ecosystems."). *See also* Moustakis Y., Nützel T., Wey H.-W., Bao W., & Pongratz J. (2024) *Temperature overshoot responses to ambitious forestation in an Earth System Model*, NAT. COMMUN. 15(1): 1–18, 9–10, ("Comparing the AR [afforestation/reforestation] pattern employed here with socioeconomic factors such as poverty, population density, governance, land tenure, and indigenous and community land is thus crucial (see "Methods", and Supplementary Fig. 10). In particular, 6.5% (61 Mha) of the AR in our scenario is applied over gridcells with a significant extent of indigenous and community land (>30%). Planting forests in these regions can often violate the will of indigenous people who can be strongly tied to their land spiritually, financially, and/or are nutritionally dependent on local food production[24], and lead to forced physical or economic displacement[98]. At the same time, 17.6% (165 Mha) of AR is deployed over regions where more than 25% of the population live below the international poverty threshold. Implementing AR over poverty-stricken regions can carry the risk of depriving people of their livelihoods and exacerbating poverty, even though positive outcomes on livelihoods have also been reported[99–101].").

[369] Pörtner H.O., *et al.* (2021) *IPBES-IPCC co-sponsored workshop report on biodiversity and climate change*, IPBES and IPCC, 16–17 ("Nature-based solutions (NbS)[3] can play an important role in climate mitigation, but the extent is debated, and they can only be effective with ambitious reductions in all human-caused greenhouse gas emissions. Nature-based solutions can be most effective when planned for longevity and not narrowly focussed on rapid carbon sequestration. Estimates of potential contributions of nature-based solutions to climate mitigation vary widely and some proposed actions such as large-scale afforestation or bioenergy plantations may violate an important tenet of nature-based solutions – namely that they should simultaneously provide human well-being and biodiversity benefits. Ecosystems can aid climate change mitigation over time, but only when complementing rapid emissions reductions in energy production, transportation, agriculture, building and industrial sectors to meet the Paris Agreement's commitment to keeping climate change well below 2°C. In addition, failing to substantially reduce emissions from

these sectors is projected to increase the climate-related risks for natural systems and reduce or limit their ability to contribute to climate change mitigation via nature-based solutions.”).

[370] Müller J. D., Gruber N., Carter B., Feely R., Ishii M., Lange N., Lauvset S. K., Murata A., Olsen A., Pérez F. F., Sabine C., Tanhua T., Wanninkhof R., & Zhu D. (2023) *Decadal Trends in the Oceanic Storage of Anthropogenic Carbon From 1994 to 2014*, AGU ADV. 4(4): 1–28, 1–2 (“Models and observation-based estimates agree that since the beginning of the industrial period, the ocean has taken up roughly 30% of the total human CO_2 emissions due to fossil fuel combustion, cement production, and land use change (Crisp et al., 2022; Friedlingstein et al., 2022; Gruber et al., 2019; Khatiwala et al., 2009, 2013; Sabine et al., 2004).”).

[371] Müller J. D., Gruber N., Carter B., Feely R., Ishii M., Lange N., Lauvset S. K., Murata A., Olsen A., Pérez F. F., Sabine C., Tanhua T., Wanninkhof R., & Zhu D. (2023) *Decadal Trends in the Oceanic Storage of Anthropogenic Carbon From 1994 to 2014*, AGU ADV. 4(4): 1–28, 13, 18 (“The global area-normalized storage sensitivity β_{area} decreased markedly and significantly, however, from 0.37 ± 0.03 mol m^{-2} ppm^{-1} for the decade 1994–2004 to 0.31 ± 0.03 mol m^{-2} ppm^{-1} during the second decade 2004–2014 (Table 1), suggesting a slowdown of the global ocean C_{ant} [anthropogenic carbon] uptake relative to what one would expect on the basis of the growth in atmospheric $\mathbf{CO_2}$.”; “For the global sensitivity β, we compute values of 1.6 ± 0.1 Pg C ppm^{-1} and 1.3 ± 0.1 Pg C ppm^{-1} for the two decades, respectively (Table 1, Figure 7). Their average confirms the long-term mean value of 1.4 ± 0.1 Pg C ppm^{-1} diagnosed by Gruber et al. (2023), but the significant decrease of about 15 ± 11% between the two decades indicates a weakening of the ocean sink for C_{ant}.”), *discussed in* Atmospheric Oceanographic and Meteorological Laboratory (17 August 2023) *Landmark study analyzes global ocean carbon storage over two decades, indicates weakening of ocean carbon sink* (“Over the 20-year period, the study finds a 15% decrease in global sensitivity as atmospheric carbon emissions increased, indicating the weakening of the ocean carbon sink for anthropogenic carbon. … Following a fundamental principle of chemistry, the ocean reaches a point at which it has accumulated substantial amounts of $\mathbf{CO_2}$ and begins to take up less additional $\mathbf{CO_2}$ (i.e. anthropogenic carbon) for a given increase in atmospheric $\mathbf{CO_2}$. The recent reduction of the “global sensitivity” determined in this study could be a first indication that the ocean will accumulate anthropogenic carbon at a reduced rate in the future, leading to more carbon in the atmosphere exacerbating climate change.”).

[372] Müller J. D., Gruber N., Carter B., Feely R., Ishii M., Lange N., Lauvset S. K., Murata A., Olsen A., Pérez F. F., Sabine C., Tanhua T., Wanninkhof R., & Zhu D. (2023) *Decadal Trends in the Oceanic Storage of Anthropogenic Carbon From 1994 to 2014*, AGU ADV. 4(4): 1–28, 18 (“The 6% decadal weakening of the ability of the surface ocean carbonate chemistry to buffer the increase in pCO_2 can explain about half of the observed decrease in the sink sensitivity β. The other half is most likely attributable to changes in the ocean's circulation and upper ocean stratification (Sallée et al., 2021) that appears to have led to a less efficient downward transport of Cant, which we discuss further in the following. … Roughly half of the decrease of the global ocean carbon sink stems from the reduced decadal storage changes in the North Atlantic (−0.9 ± 0.4 Pg C dec^{-1}). Here, we find a significant weakening of the area-normalized sink sensitivity βarea (−0.14 ± 0.04 mol m^{-2} ppm^{-1}) when comparing the first (1994–2004) to the second decade (2004–2014) of our analysis (Table 1, Figures S4 and S5 in Supporting Information S1). Furthermore, our βarea estimates for both decades are well below that obtained for the 1800–1994 period (Sabine et al., 2004), indicating a progressive weakening of the sink efficiency in the North Atlantic. The most plausible explanation for this progressive weakening is a tendency of the Atlantic Meridional Overturning Circulation (AMOC) to weaken since the 1980s (Jackson et al., 2019, 2022; Latif et al., 2022).”), *discussed in* Atmospheric Oceanographic and Meteorological Laboratory (17 August 2023) *Landmark study analyzes global ocean carbon storage over two decades, indicates weakening of ocean carbon sink* (“The second half of this weakening is attributed to changes in global ocean circulation leading to decreased transport of carbon from surface waters to the global interior ocean where it can be stored on the timescale of centuries. Specifically, a decrease in the sensitivity of the North Atlantic to act as a carbon sink is observed over the two decades and possibly due to the observed weakening of the Atlantic Meridional Overturning Circulation (AMOC), though uncertainty remains whether this weakening of the AMOC is due to natural fluctuation.”)

[373] Atmospheric Oceanographic and Meteorological Laboratory (17 August 2023) *Landmark study analyzes global ocean carbon storage over two decades, indicates weakening of ocean carbon sink* (""We will not achieve the desired outcome of decreasing emissions if we don't account for the natural sinks," explained Rik Wanninkhof, Ph.D., an author on the paper and an AOML scientist leading the Ocean Carbon Cycle Group. "As we work towards achieving net zero emissions, we are expecting natural sinks to behave the way they have in the past… and if they don't, we'll have to decrease our emissions even more than expected."").

[374] Nzotungicimpaye C. M., MacIsaac A. J., & Zickfeld K. (2023) *Delaying methane mitigation increases the risk of breaching the 2 °C warming limit*, COMMUN. EARTH. ENVIRON. 4(250): 1–8, 4 ("While anthropogenic CH_4 emissions prescribed to our model converge by the year 2100 for all considered scenarios other than SSP3-7.0 (Fig. 1), atmospheric [CH_4] levels for delayed and early CH_4 mitigation scenarios converge in the first half of the 22nd century (Fig. 2b). However, SAT differences between our mitigation scenarios persist for more than two centuries in the future (Fig. 2d), owing partly to the carbon-climate feedback (Fig. 2c and Fig. 3) as well as inertia in the climate system. These results suggest that, although CH_4 stays in the atmosphere for only about a decade, delaying CH_4 mitigation by 10–30 years will have an impact on global warming over many centuries."). *See also* Solomon S., Daniel J. S., Sanford T. J., Murphy D. M., Plattner G.-K., Knutti R., & Friedlingstein P. (2010) *Persistence of climate changes due to a range of greenhouse gases*, PROC. NAT'L. ACAD. SCI. 107(43): 18354–18359, 18358 ("For forcing agents shown in Fig. 4 with lifetimes of years to centuries, some forcing due to these gases will continue even as concentrations decay, leading to some persistence of the induced warming. Fig. 4 illustrates the persistence for HFC152a, CH_4, and N_2O, and Fig. S3 shows the behavior calculated in the Bern 2.5CC model for a range of halocarbons with lifetimes ranging from years to centuries. An important qualitative conclusion of Fig. 4 is that the warming induced by even a very short-lived gas such as HFC-152a can persist longer than the gas itself and its associated forcing (see also Figs. 3 and 4). The extent to which warming is prolonged is linked to the competition between decay of the radiative forcing and ocean heat uptake and will also depend on the carbon cycle feedback; the carbon cycle feedback and ocean heat uptake will differ somewhat among models. Persistence of the induced climate change should be expected to be larger for gases with lifetimes long enough to transfer more heat to the ocean, i.e., several decades to centuries or more, and much smaller for gases with short lifetimes of a year to a decade. Similarly, the persistence of the warming will be greater if radiative forcing is maintained over longer periods through sustained anthropogenic emissions (17, 27); i.e., the longer humans continue to emit greenhouse gases, the longer the climate memory of that emission will become, even for very short-lived substances, due to ocean thermal inertia (9).").

[375] National Oceanic and Atmospheric Administration (5 April 2024) *No sign of greenhouse gases increases slowing in 2023* ("Atmospheric methane, less abundant than CO_2 but more potent at trapping heat in the atmosphere, rose to an average of 1922.6 parts per billion (ppb). The 2023 methane increase over 2022 was 10.9 ppb, lower than the record growth rates seen in 2020 (15.2 ppb), 2021(18 ppb) and 2022 (13.2 ppb), but still the 5th highest since renewed methane growth started in 2007. Methane levels in the atmosphere are now more than 160% higher than their pre-industrial level.").

[376] Jackson R. B., Saunois M., Martinez A., Canadell J. G., Yu X., Li M., Poulter B., Raymond P. A., Regnier P., Ciais P., Davis S. J., & Patra P. K. (2024) *Human activities now fuel two-thirds of global methane emissions*, ENVIRON. RES. LETT. 19(10): 1–11, 2 ("Estimated methane emissions from inland freshwaters for the new global methane budget use new spatial products and for the first time attribute some freshwater sources to anthropogenic activities ('direct' via river damming or other human-constructed small lakes and ponds) or influences ('indirect' via eutrophication induced by enhanced nutrient loadings from the surrounding catchments). … The largest emissions sources are: wetland and inland freshwaters, agriculture and waste, and fossil fuel production and use (figure 1)."). *See also* Shindell D., Sadavarte P., Aben I., Bredariol T. de O., Dreyfus G., Höglund-Isaksson L., Poulter B., Saunois M., Schmidt G. A., Szopa S., Rentz K., Parsons L., Qu Z., Faluvegi G., & Maasakkers J. D. (2024) *The methane imperative*, FRONT. SCI. 2: 1–28, 5 ("A switch from La Niña to El Niño during 2023 appears to have reduced the observed growth rate (Figure 2), supporting a large role for wetland responses to La Niña in the very high 2020–2022 growth rates. However, emissions appear to have remained substantially higher in 2023 relative to pre-2020 values (Figure 1B), suggesting longer-term contributions from increasing anthropogenic sources along with a forced trend in natural sources. Recent work also suggests a potentially permanent shift to an altered state of enhanced wetland methane emissions (8)."); *and* Lin X., *et al.* (2024) *Recent methane surges reveal heightened emissions from tropical*

inundated areas, NAT. COMMUN. 15(1): 1–11, 5 ("In summary, the record high CH_4 growth rates in 2020 and 2021 revealed heightened emissions from inundated areas in the tropical and boreal regions. Strong and persistent emission surges were found simultaneously over the Niger River basin, the Congo basin, the Sudd swamp, the Ganges floodplains, the Southeast Asian deltas, and Hudson Bay lowlands, coincident with elevated groundwater and warming in the north, and potentially linked to La Niña conditions prevailing since 2020. Our main findings on heightened emissions from both tropical and boreal wetlands, along with evidence from other bottomup or top-down studies[10,39,53–56], suggest recent intensification of wetland methane emissions and probable strong positive wetland climate feedback[57]. In a future with warming climate (unavoidable in the Arctic) and possibly increasing occurrences of extreme or prolonged La Niña events58,59, the synchronous emission rise across boreal and tropical wetlands, as seen in 2020 and 2021 ,may occur more frequently and has the potential to accelerate atmospheric CH_4 growth. This would challenge the commitment of the Paris Agreement to limit global warming, and stresses the urgency of greater reduction in anthropogenic emissions to achieve climate mitigation goals[57,60].").

[377] Dreyfus G., Buck H., Cadillo-Quiroz H., Converse B., Hasan F., Jackson R. B., Jinnah S., Jones C. W., Leytem A., McKone T., Pang S. H., Santiesteban J. G., Stein L. Y., Turner A., Anthony K. W., & Wooldridge M. (2024) A RESEARCH AGENDA TOWARD ATMOSPHERIC METHANE REMOVAL, National Academies of Science, Engineering, and Medicine, 10 ("Currently available mitigation technologies that oxidize methane have a lower operational limit of ~1,000 parts per million (ppm). Pursuing research on methane removal at 2 ppm atmospheric methane concentrations would help lower this concentration limit as technologies are developed.").

[378] Dreyfus G., Buck H., Cadillo-Quiroz H., Converse B., Hasan F., Jackson R. B., Jinnah S., Jones C. W., Leytem A., McKone T., Pang S. H., Santiesteban J. G., Stein L. Y., Turner A., Anthony K. W., & Wooldridge M. (2024) A RESEARCH AGENDA TOWARD ATMOSPHERIC METHANE REMOVAL, National Academies of Science, Engineering, and Medicine, 4 ("For example, a technology gap exists in which no commercial mitigation technologies oxidize methane at concentrations below 1,000 parts per million (ppm) even though most methane emissions are found at concentrations closer to 2 ppm.").

[379] Dreyfus G., Buck H., Cadillo-Quiroz H., Converse B., Hasan F., Jackson R. B., Jinnah S., Jones C. W., Leytem A., McKone T., Pang S. H., Santiesteban J. G., Stein L. Y., Turner A., Anthony K. W., & Wooldridge M. (2024) A RESEARCH AGENDA TOWARD ATMOSPHERIC METHANE REMOVAL, National Academies of Science, Engineering, and Medicine, 45 ("Once the Committee identified potential high-level arguments for and against atmospheric methane removal, it further identified and considered five specific use cases for which research and/or development of atmospheric methane removal could be considered: (1) to improve methane mitigation capabilities, (2) to respond to the potential for large increases in natural emissions, (3) to close the methane emissions gap, (4) to restore atmospheric and ecological health, and (5) to develop capabilities to recover and use atmospheric methane.").

[380] Jackson R. B., Solomon E. I., Canadell J. G., Cargnello M., & Field C. B. (2019) *Methane removal and atmospheric restoration*, NAT. SUSTAIN. 2(6): 436–438, 436 ("In contrast to negative emissions scenarios for CO_2 that typically assume hundreds of billions of tonnes removed over decades and do not restore the atmosphere to preindustrial levels[7], methane concentrations could be restored to ~750 ppb by removing ~3.2 of the 5.3 Gt of CH_4 currently in the atmosphere. Rather than capturing and storing the methane, the 3.2 Gt of CH_4 could be oxidized to CO_2, a thermodynamically favourable reaction ($CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$; $\Delta Hr = –803$ kJ mol$^{–1}$). The large activation barrier associated with splitting methane's C–H bond (435 kJ mol$^{–1}$) could in principle be overcome by metal or other catalysts. In total, the reaction would yield 8.2 additional Gt of atmospheric CO_2, equivalent to a few months of current industrial CO_2 emissions[1], but it would eliminate approximately one sixth of total radiative forcing."). *See also* Jackson R. B., *et al.* (2021) *Atmospheric methane removal: a research agenda*, PHILOS. TRANS. R. SOC. A 379(2210): 1–17, 3–4 ("Atmospheric methane removal may be needed to offset continued methane release and limit the global warming contribution of this potent greenhouse gas. Eliminating most anthropogenic methane emissions is unlikely this century, and sudden methane release from the Arctic or elsewhere cannot be excluded, so technologies for negative emissions of methane may be needed. Carbon dioxide removal (CDR) has a well-established research agenda, technological foundation and comparative modelling framework [23–28]. No such framework exists for methane removal. We outline considerations for such an agenda here. We start by presenting the technological Mt CH_4 yr^{-1} considerations for methane removal: energy requirements (§2a), specific proposed technologies (§2b), and air processing and scaling

requirements (§2c). We then outline the climate and air quality impacts and feedbacks of methane removal (§3a) and argue for the creation of a Methane Removal Model Intercomparison Project (§3b), a multi-model framework that would better quantify the expected impacts of methane removal. In §4, we discuss some broader implications of methane removal."); Abernethy S., O'Connor F. M., Jones C. D., & Jackson R. B. (2021) *Methane removal and the proportional reductions in surface temperature and ozone*, PHILOS. TRANS. R. SOC. A 379(2210): 1–13, 6 ("Due to the temporal nature of effective cumulative removal, comparisons between methane and carbon dioxide depend on the timescale of interest. The equivalent of MCR for carbon dioxide, the TCRE, is 0.00048 ± 0.0001°C per Pg CO_2 [38], two orders of magnitude smaller than our MCR estimate of 0.21 ± 0.04°C per effective Pg CH_4 removed (figure 2). Accounting for the time delay for carbon dioxide removal due to the lagged response of the deep ocean, the TCRE for CO_2 removal may be even lower [39]. If 1 year of anthropogenic emissions was removed (0.36 Pg CH_4 [3] and 41.4 Pg CO_2 [40]), the transient temperature impact would be almost four times larger for methane than for CO_2 (0.075°C compared to 0.02°C). Using this example, however, maintaining a steady-state response of 0.36 Pg CH_4 effectively removed would require the ongoing removal of roughly 0.03 Pg CH_4 yr^{-1}, since a removal rate of E/τ is required to maintain an effective cumulative removal of E."); *and* Jackson R. (25 July 2024) *The Best Quick Fix for Climate Change? Curbing Methane*, THE WASHINGTON POST.

[381] Dreyfus G., Buck H., Cadillo-Quiroz H., Converse B., Hasan F., Jackson R. B., Jinnah S., Jones C. W., Leytem A., McKone T., Pang S. H., Santiesteban J. G., Stein L. Y., Turner A., Anthony K. W., & Wooldridge M. (2024) A RESEARCH AGENDA TOWARD ATMOSPHERIC METHANE REMOVAL, National Academies of Science, Engineering, and Medicine, 8 ("In this first-phase report, the Committee has identified priority research questions that should be addressed within 3–5 years. With the results from this research, a second-phase assessment could more robustly assess the viability of technologies to remove atmospheric methane at 2 ppm—from the perspective of technical, economic, and broader social viability, and the potential for climate-scale impacts. Advances in the recommended research areas and a second-phase assessment would inform any decision to move from knowledge discovery into more targeted investment in additional research, development, and/or deployment.").

[382] Abernethy S., O'Connor F. M., Jones C. D., & Jackson R. B. (2021) *Methane removal and the proportional reductions in surface temperature and ozone*, PHILOS. TRANS. R. SOC. A 379(2210): 1–13, 6 ("Due to the temporal nature of effective cumulative removal, comparisons between methane and carbon dioxide depend on the timescale of interest. The equivalent of MCR for carbon dioxide, the TCRE, is 0.00048 ± 0.0001°C per Pg CO_2 [38], two orders of magnitude smaller than our MCR estimate of 0.21 ± 0.04°C per effective Pg CH_4 removed (figure 2). Accounting for the time delay for carbon dioxide removal due to the lagged response of the deep ocean, the TCRE for CO_2 removal may be even lower [39]. If 1 year of anthropogenic emissions was removed (0.36 Pg CH_4 [3] and 41.4 Pg CO_2 [40]), the transient temperature impact would be almost four times larger for methane than for CO_2 (0.075°C compared to 0.02°C). Using this example, however, maintaining a steady-state response of 0.36 Pg CH_4 effectively removed would require the ongoing removal of roughly 0.03 Pg CH_4 yr^{-1}, since a removal rate of E/τ is required to maintain an effective cumulative removal of E."), *discussed in* Jordan R. (26 September 2021) *Stanford-led research reveals potential of an overlooked climate change solution*, Stanford Woods Institute for the Environment ("The analyses, published Sept. 27 in Philosophical Transactions of the Royal Society A, reveal that removing about three years-worth of human caused emissions of the potent greenhouse gas would reduce global surface temperatures by approximately 0.21 degrees Celsius while reducing ozone levels enough to prevent roughly 50,000 premature deaths annually. The findings open the door to direct comparisons with carbon dioxide removal – an approach that has received significantly more research and investment – and could help shape national and international climate policy in the future. […] Under a high emissions scenario, the analysis showed that a 40 percent reduction in global methane emissions by 2050 would lead to a temperature reduction of approximately 0.4 degrees Celsius by 2050. Under a low emissions scenario where temperature peaks during the 21st century, methane removal of the same magnitude could reduce the peak temperature by up to 1 degree Celsius.").

[383] Dreyfus G., Buck H., Cadillo-Quiroz H., Converse B., Hasan F., Jackson R. B., Jinnah S., Jones C. W., Leytem A., McKone T., Pang S. H., Santiesteban J. G., Stein L. Y., Turner A., Anthony K. W., & Wooldridge M. (2024) A RESEARCH AGENDA TOWARD ATMOSPHERIC METHANE REMOVAL, National Academies of Science, Engineering, and Medicine, 6 (*see* Table S-1 "Summary of the State of Atmospheric Methane Removal Technology Research Relative to 2 Parts Per Million (ppm) Atmospheric Methane Concentrations").

[384] Dreyfus G., Buck H., Cadillo-Quiroz H., Converse B., Hasan F., Jackson R. B., Jinnah S., Jones C. W., Leytem A., McKone T., Pang S. H., Santiesteban J. G., Stein L. Y., Turner A., Anthony K. W., & Wooldridge M. (2024) A RESEARCH AGENDA TOWARD ATMOSPHERIC METHANE REMOVAL, National Academies of Science, Engineering, and Medicine, 2 (*see* Box S-1 "Key Definitions and Atmospheric Methane Removal Technologies Considered in This Report").

[385] Krogsbøll M., Russell H. S., & Johnson M. S. (2023) *A high efficiency gas phase photoreactor for eradication of methane from low-concentration sources*, ENVIRON. RES. LETT. 19(1): 014017, 1–7, 1 ("Despite the urgent need, very few methods are able to efficiently remove methane from waste air with low cost and energy per unit volume, especially at the low concentrations found in emissions from e.g. wastewater treatment, livestock production, biogas production and mine ventilation. We present the first results of a novel method based on using chlorine atoms in the gas phase, thereby achieving high efficiency. A laboratory prototype of the methane eradication photochemical system (MEPS) technology achieves 58% removal efficiency with a flow capacity of 30 l min^{-1}; a reactor volume of 90 l; UV power input at 368 nm of 110 W; chlorine concentration of 99 ppm; and a methane concentration of 55 ppm; under these conditions the apparent quantum yield (AQY) ranged from 0.48% to 0.56% and the volumetric energy consumption ranged from 36 to 244 kJ m−3. The maximum achieved AQY with this system was 0.83%. A series of steps that can be taken to further improve performance are described. These metrics show that MEPS has the potential to be a viable method for eliminating low-concentration methane from waste air."). *See also* Brenneis R. J., Johnson E. P., Shi W., & Plata D. L. (2022) *Atmospheric- and Low-Level Methane Abatement via an Earth-Abundant Catalyst*, ACS Environ. Au 2(3): 223–31, 223 ("Here, we describe the use of a biomimetic copper zeolite capable of converting atmospheric- and low-level methane at relatively low temperatures (e.g., 200−300 °C) in simulated air.").

[386] Dreyfus G., Buck H., Cadillo-Quiroz H., Converse B., Hasan F., Jackson R. B., Jinnah S., Jones C. W., Leytem A., McKone T., Pang S. H., Santiesteban J. G., Stein L. Y., Turner A., Anthony K. W., & Wooldridge M. (2024) A RESEARCH AGENDA TOWARD ATMOSPHERIC METHANE REMOVAL, National Academies of Science, Engineering, and Medicine, 4–5.

[387] Dreyfus G., Buck H., Cadillo-Quiroz H., Converse B., Hasan F., Jackson R. B., Jinnah S., Jones C. W., Leytem A., McKone T., Pang S. H., Santiesteban J. G., Stein L. Y., Turner A., Anthony K. W., & Wooldridge M. (2024) A RESEARCH AGENDA TOWARD ATMOSPHERIC METHANE REMOVAL, National Academies of Science, Engineering, and Medicine, 9 ("The Committee suggests that a reasonable initial investment in basic science that would help society understand the prospects of atmospheric methane removal is in the range of $50 million–80 million per year over 3–5 years. A research program of this size would advance the five research areas recommended to inform a phase-two assessment.").

[388] Dreyfus G., Buck H., Cadillo-Quiroz H., Converse B., Hasan F., Jackson R. B., Jinnah S., Jones C. W., Leytem A., McKone T., Pang S. H., Santiesteban J. G., Stein L. Y., Turner A., Anthony K. W., & Wooldridge M. (2024) A RESEARCH AGENDA TOWARD ATMOSPHERIC METHANE REMOVAL, National Academies of Science, Engineering, and Medicine, 119 ("In both phases, the recommended research areas should be integrative and transdisciplinary. By integrative, the Committee means research in which knowledge from different disciplines is integrative, perhaps evolving into a shared set of methods and concepts that comes to be used by collaborators. "Transdisciplinary" can refer to interaction between disciplines in defining the research but often includes other features: research that is socially engaged, reflexive, and focuses on real-world problems (Lawrence et al., 2022). Atmospheric methane removal falls into the broad categories of "wicked problems" or "grand challenges" within sustainability science—complex socioecological problems that demand working beyond disciplinary silos (Sundstrom et al., 2023)."); 139 ("There are broad calls across multiple literatures for community and/or public engagement efforts to be part of research efforts when research has potentially important social impacts (see Chapter 5). This may include but also extends well beyond research on emerging technologies, such as atmospheric methane removal and other climate intervention approaches. These calls for engagement are often rooted in claims for environmental justice and the imperative to involve those impacted by decisions in the decision-making process as well as for rights-based arguments and those which are more instrumental in nature (see Chapter 4). Recent research further suggests that early

deliberative engagement can mitigate social impacts, especially in the context of emerging technology development (Grubert, 2024).").

[389] Dreyfus G., Buck H., Cadillo-Quiroz H., Converse B., Hasan F., Jackson R. B., Jinnah S., Jones C. W., Leytem A., McKone T., Pang S. H., Santiesteban J. G., Stein L. Y., Turner A., Anthony K. W., & Wooldridge M. (2024) A RESEARCH AGENDA TOWARD ATMOSPHERIC METHANE REMOVAL, National Academies of Science, Engineering, and Medicine, 156 ("A foundational conclusion of this report is that atmospheric methane removal approaches, if successfully developed, could not replace methane emissions mitigation on timescales relevant to limiting peak warming this century. Another key conclusion is that potential exists for a substantial methane emissions gap due in part to large, growing, primarily natural methane emissions sources, for which no mitigation options currently exist.").

[390] Lenton T. M., Rockstrom J., Gaffney O., Rahmstorf S., Richardson K., Steffen W., & Schellnhuber H. J. (2019) *Climate tipping points—too risky to bet against*, Comment, NATURE, 575(7784): 592–595, 594 ("In our view, the clearest emergency would be if we were approaching a global cascade of tipping points that led to a new, less habitable, 'hothouse' climate state[11]. Interactions could happen through ocean and atmospheric circulation or through feedbacks that increase greenhouse-gas levels and global temperature. Alternatively, strong cloud feedbacks could cause a global tipping point[12,13].We argue that cascading effects might be common. Research last year[14] analysed 30 types of regime shift spanning physical climate and ecological systems, from collapse of the West Antarctic ice sheet to a switch from rainforest to savanna. This indicated that exceeding tipping points in one system can increase the risk of crossing them in others. Such links were found for 45% of possible interactions[14]. In our view, examples are starting to be observed. … If damaging tipping cascades can occur and a global tipping point cannot be ruled out, then this is an existential threat to civilization. No amount of economic cost–benefit analysis is going to help us. We need to change our approach to the climate problem. … In our view, the evidence from tipping points alone suggests that we are in a state of planetary emergency: both the risk and urgency of the situation are acute…."). *See also* Armstrong McKay D. I., Staal A., Abrams J. F., Winkelmann R., Sakschewski B., Loriani S., Fetzer I., Cornell S. E., Rockström J., & Lenton T. M. (2022) *Exceeding 1.5°C global warming could trigger multiple climate tipping points*, SCIENCE 377(6611): 1–10, 7 ("Current warming is ~1.1°C above preindustrial and even with rapid emission cuts warming will reach ~1.5°C by the 2030s (23). We cannot rule out that WAIS and GrIS tipping points have already been passed (see above) and several other tipping elements have minimum threshold values within the 1.1 to 1.5°C range. Our best estimate thresholds for GrIS, WAIS, REEF, and abrupt permafrost thaw (PFAT) are ~1.5°C although WAIS and GrIS collapse may still be avoidable if GMST returns below 1.5°C within an uncertain overshoot time (likely decades) (94).").

[391] Hoegh-Guldberg O., *et al.* (2018) *Chapter 3: Impacts of 1.5°C of Global Warming on Natural and Human Systems*, *in* GLOBAL WARMING OF 1.5 °C, *Special Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 262 ("Tipping points refer to critical thresholds in a system that, when exceeded, can lead to a significant change in the state of the system, often with an understanding that the change is irreversible. An understanding of the sensitivities of tipping points in the physical climate system, as well as in ecosystems and human systems, is essential for understanding the risks associated with different degrees of global warming. This subsection reviews tipping points across these three areas within the context of the different sensitivities to 1.5°C versus 2°C of global warming. Sensitivities to less ambitious global temperature goals are also briefly reviewed. Moreover, an analysis is provided of how integrated risks across physical, natural and human systems may accumulate to lead to the exceedance of thresholds for particular systems. The emphasis in this section is on the identification of regional tipping points and their sensitivity to 1.5°C and 2°C of global warming, whereas tipping points in the global climate system, referred to as large-scale singular events, were already discussed in Section 3.5.2. A summary of regional tipping points is provided in Table 3.7."); *and* Abram N., *et al.* (2019) *Chapter 1: Framing and Context of the Report*, *in* THE OCEAN AND CRYOSPHERE IN A CHANGING CLIMATE, *Special Report of the Intergovernmental Panel on Climate Change*, Pörtner H.-O., *et al.* (eds.), 1-81 ("While some aspects of the ocean and cryosphere might respond in a linear (i.e., directly proportional) manner to a perturbation by some external forcing, this may change fundamentally when critical thresholds are reached. A very important example for such a threshold is the transition from frozen water to liquid water at around 0 ºC that can lead to rapid acceleration of ice-melt or permafrost thaw (e.g., Abram et al., 2013; Trusel et al., 2018). Such thresholds often act as tipping points, as they are associated with rapid and abrupt changes even when the underlying forcing changes gradually (Figure 1.1a, 1.1c). Tipping elements include, for example, the collapse of the ocean's large-scale overturning circulation in the Atlantic (Section 6.7), or the collapse of the West

Antarctic Ice Sheet though a process called marine ice sheet instability (Cross-Chapter Box 8 in Chapter 3; Lenton, *et al*. 2008). Potential ocean and cryosphere tipping elements form part of the scientific case for efforts to limit climate warming to well below 2ºC (IPCC, 2018).").

[392] Drijfhout S., Bathiany S., Beaulieu C., Brovkin V., Claussen M., Huntingford C., Scheffer M., Sgubin G., & Swingedouw D. (2015) *Catalogue of abrupt shifts in Intergovernmental Panel on Climate Change climate models*, PROC. NAT'L. ACAD. SCI. 112(43): E5777–E5786, E5784, E5777 (Figure 4 shows 6 abrupt events between 1.0–1.5°C and 11 between 1.5–2.0°C; "Abrupt transitions of regional climate in response to the gradual rise in atmospheric greenhouse gas concentrations are notoriously difficult to foresee. However, such events could be particularly challenging in view of the capacity required for society and ecosystems to adapt to them. We present, to our knowledge, the first systematic screening of the massive climate model ensemble informing the recent Intergovernmental Panel on Climate Change report, and reveal evidence of 37 forced regional abrupt changes in the ocean, sea ice, snow cover, permafrost, and terrestrial biosphere that arise after a certain global temperature increase. Eighteen out of 37 events occur for global warming levels of less than 2°, a threshold sometimes presented as a safe limit."). *See also* Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, REV. GEOPHYS. 61(e2021RG000757): 1–81, 48 ("Earth system elements that this review indicates are at higher risk of crossing critical thresholds or undergoing substantial changes in response to warming this century under moderate (RCP4.5) emissions scenarios include loss of Arctic summer sea ice, loss of portions of the GIS, loss of portions of the West Antarctic Ice-sheet, Amazon rainforest dieback, boreal forest ecosystem shifts, some permafrost carbon release, and coral reef loss (Figure 14). In contrast, methane release from marine methane hydrates and strato-cumulus cloud deck evaporation will likely require longer timescales and higher emissions forcing in order to occur at large scales, while disruptions of tropical monsoons may be contingent on large shifts in other Earth system components and are unlikely to occur as a direct response to changes in aerosol forcing or land cover (see Section 2.6). Critical thresholds for weakening of the AMOC remain unclear and a transition of this system to a different state may not occur this century (see Section 2.1). While the GIS and WAIS may transgress critical thresholds this century (see Section 2.3), timescales of ice loss may require many centuries to millennia to run to completion (Bakker et al., 2016; Clark et al., 2016; Golledge et al., 2015; Huybrechts & De Wolde, 1999)."); Lenton T. M., Rockstrom J., Gaffney O., Rahmstorf S., Richardson K., Steffen W., & Schellnhuber H. J. (2019) *Climate tipping points—too risky to bet against*, Comment, NATURE 575(7784): 592–595, 593 ("A further key impetus to limit warming to 1.5 °C is that other tipping points could be triggered at low levels of global warming. The latest IPCC models projected a cluster of abrupt shifts between 1.5 °C and 2 °C, several of which involve sea ice. This ice is already shrinking rapidly in the Arctic…"); Arias P. A., *et al.* (2021) *Technical Summary*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), TS-71–TS-72 ("It is *likely* that under stabilization of global warming at 1.5°C, 2.0°C, or 3.0°C relative to 1850–1900, the AMOC will continue to weaken for several decades by about 15%, 20% and 30% of its strength and then recover to pre-decline values over several centuries (*medium confidence*). At sustained warming levels between 2°C and 3°C, there is limited evidence that the Greenland and West Antarctic Ice Sheets will be lost almost completely and irreversibly over multiple millennia; both the probability of their complete loss and the rate of mass loss increases with higher surface temperatures (*high confidence*). At sustained warming levels between 3°C and 5°C, near-complete loss of the Greenland Ice Sheet and complete loss of the West Antarctic Ice Sheet is projected to occur irreversibly over multiple millennia (*medium confidence*); with substantial parts or all of Wilkes Subglacial Basin in East Antarctica lost over multiple millennia (*low confidence*). Early-warning signals of accelerated sea-level-rise from Antarctica, could possibly be observed within the next few decades. For other hazards (e.g., ice sheet behaviour, glacier mass loss and global mean sea level change, coastal floods, coastal erosion, air pollution, and ocean acidification) the time and/or scenario dimensions remain critical, and a simple and robust relationship with global warming level cannot be established (*high confidence*) … The response of biogeochemical cycles to anthropogenic perturbations can be abrupt at regional scales and irreversible on decadal to century time scales (*high confidence*). The probability of crossing uncertain regional thresholds increases with climate change (*high confidence*). It is *very unlikely* that gas clathrates (mostly methane) in deeper terrestrial permafrost and subsea clathrates will lead to a detectable departure from the emissions trajectory during this century. Possible abrupt changes and tipping points in biogeochemical cycles lead to additional uncertainty in 21st century atmospheric GHG concentrations, but future anthropogenic emissions remain the dominant uncertainty (*high confidence*). There is potential for abrupt water cycle

changes in some high-emission scenarios, but there is no overall consistency regarding the magnitude and timing of such changes. Positive land surface feedbacks, including vegetation, dust, and snow, can contribute to abrupt changes in aridity, but there is only *low confidence* that such changes will occur during the 21st century. Continued Amazon deforestation, combined with a warming climate, raises the probability that this ecosystem will cross a tipping point into a dry state during the 21st century (*low confidence*)."); *and* Lee J.-Y., Marotzke J., Bala G., Cao L., Corti S., Dunne J. P., Engelbrecht F., Fischer E., Fyfe J. C., Jones C., Maycock A., Mutemi J., Ndiaye O., Panickal S., & T. Zhou (2021) *Chapter 4: Future Global Climate: Scenario-Based Projections and Near-Term Information*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 4-96 (Table 4.10 lists 15 components of the Earth system susceptible to tipping points).

[393] *See* Hoegh-Guldberg O., *et al.* (2018) *Chapter 3: Impacts of 1.5°C of Global Warming on Natural and Human Systems*, *in* GLOBAL WARMING OF 1.5 °C, *Special Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 262 ("Tipping points refer to critical thresholds in a system that, when exceeded, can lead to a significant change in the state of the system, often with an understanding that the change is irreversible. An understanding of the sensitivities of tipping points in the physical climate system, as well as in ecosystems and human systems, is essential for understanding the risks associated with different degrees of global warming. This subsection reviews tipping points across these three areas within the context of the different sensitivities to 1.5°C versus 2°C of global warming. Sensitivities to less ambitious global temperature goals are also briefly reviewed. Moreover, an analysis is provided of how integrated risks across physical, natural and human systems may accumulate to lead to the exceedance of thresholds for particular systems. The emphasis in this section is on the identification of regional tipping points and their sensitivity to 1.5°C and 2°C of global warming, whereas tipping points in the global climate system, referred to as large-scale singular events, were already discussed in Section 3.5.2. A summary of regional tipping points is provided in Table 3.7."); *and* Abram N., *et al.* (2019) *Chapter 1: Framing and Context of the Report*, *in* THE OCEAN AND CRYOSPHERE IN A CHANGING CLIMATE, *Special Report of the Intergovernmental Panel on Climate Change*, Pörtner H.-O., *et al.* (eds.), 1-81 ("While some aspects of the ocean and cryosphere might respond in a linear (i.e., directly proportional) manner to a perturbation by some external forcing, this may change fundamentally when critical thresholds are reached. A very important example for such a threshold is the transition from frozen water to liquid water at around 0 ºC that can lead to rapid acceleration of ice-melt or permafrost thaw (e.g., Abram et al., 2013; Trusel et al., 2018). Such thresholds often act as tipping points, as they are associated with rapid and abrupt changes even when the underlying forcing changes gradually (Figure 1.1a, 1.1c). Tipping elements include, for example, the collapse of the ocean's large-scale overturning circulation in the Atlantic (Section 6.7), or the collapse of the West Antarctic Ice Sheet though a process called marine ice sheet instability (Cross-Chapter Box 8 in Chapter 3; Lenton, *et al*. 2008). Potential ocean and cryosphere tipping elements form part of the scientific case for efforts to limit climate warming to well below 2ºC (IPCC, 2018).").

[394] Here we distinguish between abrupt shifts, as in Drijfhout *et al*. (2015), and the more restrictive definition of "core climate tipping points" defined by Armstrong McKay *et al.* (2022) as "when change in part of the climate system becomes (i) selfperpetuating beyond (ii) a warming threshold as a result of asymmetry in the relevant feedbacks, leading to (iii) substantial and widespread Earth system impacts." *See* Armstrong McKay D. I., Staal A., Abrams J. F., Winkelmann R., Sakschewski B., Loriani S., Fetzer I., Cornell S. E., Rockström J., & Lenton T. M. (2022) *Exceeding 1.5°C global warming could trigger multiple climate tipping points*, SCIENCE 377(6611): 1–10, 7 ("Current warming is ~1.1°C above preindustrial and even with rapid emission cuts warming will reach ~1.5°C by the 2030s (23). We cannot rule out that WAIS [West Antarctic Ice Sheet] and GrIS [Greenland Ice Sheet] tipping points have already been passed (see above) and several other tipping elements have minimum threshold values within the 1.1 to 1.5°C range. Our best estimate thresholds for GrIS, WAIS, REEF [low-latitude coral reefs], and North Atlantic subpolar gyre / Labrador-Irminger Sea convection abrupt permafrost thaw (PFAT) are ~1.5°C although WAIS and GrIS collapse may still be avoidable if GMST [Global Mean Surface Temperature] returns below 1.5°C within an uncertain overshoot time (likely decades) (94). … The chance of triggering CTPs [Climate tipping points] is already non-negligible and will grow even with stringent climate mitigation (SSP1-1.9 in Fig. 2, B and C). Nevertheless, achieving the Paris Agreement's aim to pursue efforts to limit warming to 1.5°C would clearly be safer than keeping global warming below 2°C (90) (Fig. 2). Going from 1.5 to 2°C increases the likelihood of committing to WAIS and GrIS collapse near complete warm-water coral die-off, and abrupt permafrost thaw; further, the best estimate threshold

for LABC [North Atlantic subpolar gyre / Labrador-Irminger Sea convection] collapse is crossed. The likelihood of triggering AMOC [Atlantic Meridional Overturning Circulation] collapse, Boreal forest shifts, and extra-polar glacier loss becomes non-negligible at >1.5°C and glacier loss becomes likely by ~2°C. A cluster of abrupt shifts occur in ESM [Earth System Models] at 1.5 to 2°C (19). Although not tipping elements, ASSI [Arctic Summer Sea Ice] loss could become regular by 2°C, gradual permafrost thaw would likely become widespread beyond 1.5°C, and land carbon sink weakening would become significant by 2°C."); Drijfhout S., Bathiany S., Beaulieu C., Brovkin V., Claussen M., Huntingford C., Scheffer M., Sgubin G., & Swingedouw D. (2015) *Catalogue of abrupt shifts in Intergovernmental Panel on Climate Change climate models*, PROC. NAT'L. ACAD. SCI. 112(43): E5777–E5786, E5778 ("Firstly, we systematically screen the CMIP5 multimodel ensemble of simulations for evidence of abrupt changes using search criteria (Methods) to make a first filtering of regions of potentially relevant abrupt events from this dataset (stage 1). These criteria are motivated by the definition of the assessment report, AR5 (4): "A large-scale change in the climate system that takes place over a few decades or less, persists (or is anticipated to persist) for at least a few decades, and causes substantial disruptions in human and natural systems." Other definitions have emphasized the timescales of the change, e.g., 30 y (10), and rapidity in comparison with the forcing (11), which also meet our search criteria."); *and* Intergovernmental Panel on Climate Change (2023) AR6 SYNTHESIS REPORT: CLIMATE CHANGE 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 42 ("Risks associated with large-scale singular events or tipping points, such as ice sheet instability or ecosystem loss from tropical forests, transition to high risk between 1.5°C–2.5°C (*medium confidence*) and to very high risk between 2.5°C–4°C (*low confidence*). The response of biogeochemical cycles to anthropogenic perturbations can be abrupt at regional scales and irreversible on decadal to century time scales (*high confidence*). The probability of crossing uncertain regional thresholds increases with further warming (*high confidence*).").

[395] Möller T., Högner A., Schleussner C.-F., Bien S., Kitzmann N., Lamboll R., Rogelj J., Donges J., Rockström J., & Wunderling N. (2024) *Achieving net zero greenhouse gas emissions critical to limit climate tipping risks*, NAT. COMMUN. 15(1): 1–11, 5 ("The contributions of the individual tipping elements to overall tipping risk increase are resolved in Fig. 5b. We find that while AMOC is the main driver of tipping risk increase at lower mean peak temperatures, the AMAZ is the main driver of the non-linear acceleration in tipping risk above 2.0 °C mean peak temperature. This can be explained by the onset of the AMAZ tipping threshold range at 2.0 °C (see Supplementary Table 1). However, the non-linear acceleration at ~2.0 °C mean peak temperature is also observed for the other tipping elements to smaller degrees (see also Supplementary Fig. 6b). As an AMAZ tipping does not drive interactions in our model (compare Fig. 2c), network effects enhancing this behaviour are driven by ice sheet or AMOC tipping (see Supplementary Fig. 6 for the impact of interactions).").

[396] McIntyre M. E. (2023) *Climate tipping points: A personal view*, PHYSICS TODAY 76(3): 44–49, 45–46 ("Nearly all the climate system's real complexity is outside the scope of any model, whether it's a global climate model that aims to represent the climate system as a whole or a model that only simulates the carbon cycle, ice flow, or another subsystem…. Changes taking only a few years are almost instantaneous from a climate-system perspective. They're a warning to take seriously the possibility of tipping points in the dynamics of the real climate system.[9] The warning is needed because some modelers have argued that tipping points are less probable for the real climate system than for the simplified, low-order climate models studied by dynamic-systems researchers.[3] Other researchers, however, have suggested that such a tipping point may be reached sometime in the next few decades or even sooner.[6,7] Some of its mechanisms resemble those of the Dansgaard–Oeschger warmings and would suddenly accelerate the rate of disappearance of Arctic sea ice. As far as I am aware, no such tipping points have shown up in the behavior of the biggest and most sophisticated climate models. The suggested tipping-point behavior depends on fine details that are not well resolved in the models, including details of the sea ice and the layering of the upper ocean. Also of concern are increases in the frequency and intensity of destructive weather extremes. Such increases have already been observed in recent years. Climate scientists are asking how much further the increases will go and precisely how they will develop. That question is, of course, bound up with the question of tipping points. A failure to simulate many of the extremes themselves, especially extremes of surface storminess, must count as another limitation of the climate models. The reasons are related to the resolution constraints of climate models."). *See also* Spratt D. (19 April 2023) *Faster than forecast, climate impacts trigger tipping points in the Earth system*, BULLETIN OF THE ATOMIC SCIENTISTS

(“While observed warming has been close to climate model projections, the impacts have in many instances been faster and even more extreme than the models forecasted. William Ripple and his co-researchers show that many positive feedbacks are not fully accounted for in climate models…. In September 2022, Stockholm University’s David Armstrong McKay and his colleagues concluded that even global warming of 1-degree Celsius risks triggering some tipping points, just one data point in an alarming mountain of research on tipping points presented in the last year and a half. … Speaking in 2018, Steffen said that the dominant linear, deterministic framework for assessing climate change is flawed, especially at higher levels of temperature rise. Model projections that don’t include these feedback and cascading processes “become less useful at higher temperature levels… or, as my co-author John Schellnhuber says, we are making a big mistake when we think we can ‘park’ the Earth System at any given temperature rise – say 2°C – and expect it to stay there.”); Ripple W. J., Wolf C., Lenton T. M., Gregg J. W., Natali S. M., Duffy P. B., Rockström J., & Schellnhuber H. J. (2023) *Many risky feedback loops amplify the need for climate action*, ONE EARTH 6(2): 86–91, 87, 89 (“Moreover, because climate feedbacks can interact with each other and exhibit temperature dependence[9,10] and non-linearities, currently weak feedbacks have the potential to become stronger, following warming driven by other feedback loops. In a grim scenario, interacting feedback loops could result in a sequence of climate tipping points being exceeded,[5,11] producing ‘‘climate cascades,’’ whereby the net effect of reinforcing feedbacks is greater than the sum of their individual effects under current conditions.”; “Biological feedback loops involving forest dieback, loss of soil carbon, thawing permafrost, drying and smoldering peatlands, and the changing ocean biological pump are highly uncertain and may be large.”); *and* Ben Santer, Henry Jacoby, Richard Richels, & Gary Yohe (28 November 2023) *Tipping into the danger zone — we need to learn more about climate tipping points*, THE HILL (“The scientific and policy concern is that by burning fossil fuels and warming the planet, humanity is moving ever closer to triggering multiple climate tipping points. Yet our understanding of how near we are to those events is still disturbingly uncertain. … Model simulations of 21st century climate change can tell us how close we might be to passing tipping points, and what physical processes might kick in as we approach them. Models, however, have their own problems. Although they are the product of many decades of scientific development, involving thousands of scientists around the globe, models represent the incredibly complex real-world climate system in simplified numerical form. There will always be climate processes “lost in translation” of that complex reality into computer code. Furthermore, the divergent modeling approaches used by different researchers contribute to uncertainty in what models tell us about how fast are we approaching tipping points.”).

[397] Lenton T. M., Rockstrom J., Gaffney O., Rahmstorf S., Richardson K., Steffen W., & Schellnhuber H. J. (2019) *Climate tipping points—too risky to bet against*, Comment, NATURE 575(7784): 592–595, 594 (“In our view, the clearest emergency would be if we were approaching a global cascade of tipping points that led to a new, less habitable, ‘hothouse’ climate state[11]. Interactions could happen through ocean and atmospheric circulation or through feedbacks that increase greenhouse-gas levels and global temperature.”). *See also* Wunderling N., *et al.* (2024) *Climate tipping point interactions and cascades: a review*, EARTH SYST. DYNAM. 15(1): 41–74, 43 (“The most extreme case is the situation in which the tipping of element A causes a subsequent tipping of element B. In this paper, we define a sequence of events involving several nonlinear components of the Earth system as tipping cascades (Dekker et al., 2018; Wunderling et al., 2021a). These tipping cascades can come in various forms dependent on the ordering of tipping elements (e.g., Klose et al., 2021) and can be different depending on the bifurcations (e.g., Hopf or fold bifurcation) present in the individual tipping elements (Dekker et al., 2018). Eventually a tipping cascade might result in a fundamental change in the Earth’s equilibrium climate. It is important to note that interactions between tipping elements are not all monotonically constant but may also change depending on the current state of the involved tipping elements (e.g., interactions can be nonstationary) or may affect different parts of a particular tipping element in a different way. Since knowledge at this level of detail in the interactions is very heterogeneous and sparse, we will use the above definition of tipping linkages and cascades in this paper.”); Wunderling N., Donges J. F., Kurths J., & Winkelmann R. (2021) *Interacting tipping elements increase risk of climate domino effects under global warming*, EARTH SYST. DYN. 12(2): 601–619, 614 (“In this study, we show that this risk increases significantly when considering interactions between these climate tipping elements and that these interactions tend to have an overall destabilising effect. Altogether, with the exception of the Greenland Ice Sheet, interactions effectively push the critical threshold temperatures to lower warming levels, thereby reducing the overall stability of the climate system. The domino-like interactions also foster cascading, non-linear responses. Under these circumstances, our model indicates that cascades are predominantly initiated by the polar ice sheets and mediated by the AMOC. Therefore, our results also imply that the negative feedback loop connecting the Greenland Ice Sheet and the AMOC might not be able to stabilise the

climate system as a whole."); *and* Ripple W. J., Wolf C., Gregg J. W., Rockström J., Mann M. E., Oreskes N., Lenton T. M., Rahmstorf S., Newsome T. M., Xu C., Svenning J.-C., Pereira C. C., Law B. E., & Crowther T. W. (2024) *The 2024 state of the climate report: Perilous times on planet Earth*, BIOSCI.: 1–13, 9 ("Tipping elements are biophysical systems on Earth with tipping point behavior that contribute to regulating the climate system (Lenton et al. 2008). They have recently been assessed for their tipping sensitivity. Five of sixteen climate tipping elements are likely to cross their tipping points at 1.5°C: the Greenland ice sheet, the West Antarctic ice sheet, boreal permafrost, low-latitude coral reefs, and the Barents Sea Ice (Armstrong McKay et al. 2022). Several climate tipping elements are connected, and if one tips, others may tip, triggering a tipping point cascade (Wunderling et al. 2024). Overall, this points to a complex situation where climate controlling feedback loops and tipping point systems are interconnected in a way that could trigger self-perpetuating processes that amplify warming beyond human control.").

[398] Ritchie P. D. L., Alkhayuon H., Cox P. M., & Wieczorek S. (2023) *Rate-induced tipping in natural and human systems*, EARTH SYST. DYN. 14(3): 669–683, 669–670, 678 ("However, there is another, less obvious potential consequence of changes in external forcing. When an external forcing changes faster than some critical rate rather than necessarily by a large amount, this can lead to rate-induced tipping points (Stocker and Schmittner, 1997; Luke and Cox, 2011; Wieczorek et al., 2011; Ashwin et al., 2012; Ritchie and Sieber, 2016; Siteur et al., 2016; Suchithra et al., 2020; Arumugam et al., 2020; Pierini and Ghil, 2021; Wiec- zorek et al., 2023; Longo et al., 2021; Kuehn and Longo, 2022; Kaur and Sharathi Dutta, 2022; Hill et al., 2022; Arnscheidt and Rothman, 2022). In contrast to bifurcation-induced tipping, rate-induced tipping occurs due to fast-enough changes in external forcing and usually does not exceed any critical levels as a result of external forcing. Such tipping points are much less widely known and yet are arguably even more relevant to contemporary issues such as climate change (Lohmann and Ditlevsen, 2021; Clarke et al., 2021; O'Sullivan et al., 2022), ecosystem collapse (Scheffer et al., 2008; Vanselow et al., 2019; van der Bolt and van Nes, 2021; Neijnens et al., 2021; Vanselow et al., 2022), and the resilience of human systems (Witthaut et al., 2021)."); ("This paper highlights the importance of considering how fast external forcing is changing as opposed to solely focusing on levels of change. Consequently, the actions taken to control the rate of change in forcing are equally as important as the actions taken to control the level at which forcing is halted."), *discussed in* Morrison A. (14 July 2023) *Tipping Points Can Be Triggered Unexpectedly By Dangerous Rates Of Change*, UNIVERSITY OF EXETER NEWS ("Until now, critical thresholds have been assumed to be a point of no return, but the new study – published in the journal *Earth System Dynamics* – concludes that dangerous rates could trigger permanent shifts in human and natural systems before these critical levels are reached…Whilst the latest Intergovernmental Panel on Climate Change 6th Assessment Report rightly highlighted the urgency to limit global warming levels, it fell short of identifying the rate of warming as a key risk factor for climate tipping points" said joint lead author Dr Paul Ritchie, of Exeter's Global Systems Institute and the Department of Mathematics and Statistics."). For information on how the timescales over which tipping occurs and the rates of environmental change may interact to determine whether tipping cascades occur, *see* Klose A. K., Donges J. F., Feudel U., & Winkelmann R. (2024) *Rate-induced tipping cascades arising from interactions between the Greenland Ice Sheet and the Atlantic Meridional Overturning Circulation*, EARTH SYS. DYNAM. 15: 635–652, 645 ("Our results stress that the interplay of applied external and corresponding internal forcing time scales relative to the response time scales of the tipping elements is of importance for interacting tipping elements of the climate system as theses time scales may eventually determine the tipping dynamics. … This implies that safe pathways for the evolution of tipping element drivers preventing cascading tipping and their boundary to dangerous pathways involving cascades are controlled by rates of changes of the responsible control parameters in addition to their magnitude. Hence, our model qualitatively suggests that it is not only necessary to stay below critical thresholds in terms of the magnitude of some environmental condition (Schellnhuber et al., 2016) as intended by the Paris Agreement (UNFCCC, 2015) to hinder tipping cascades. In addition, it is required to respect safe rates of environmental change to mitigate domino effects as concluded previously for individual tipping elements (Ashwin et al., 2012; Luke and Cox, 2011; Petschel-Held et al., 1999; Stocker and Schmittner, 1997; Wieczorek et al., 2011; Schoenmakers and Feudel, 2021)").

[399] Willcock S., Cooper G. S., Addy J., & Dearing J. A. (2023) *Earlier collapse of Anthropocene ecosystems driven by multiple faster and noisier drivers*, NAT SUSTAIN: 1–12, 3, 4, 5 ("In addition to earlier breakpoint dates, extra drivers can also cause ATDCs [Abrupt Threshold-Dependent Change] at levels where it would be resilient to the primary slow driver in isolation (Supplementary Section 2)"; "The addition of high noise (normalized $\sigma > 0.666$) shows that increasing the variability of the primary slow driver (in isolation) across all four models can bring forward

the date of system collapse (Fig. 3). The effects outlined above are synergistic—combining multiple drivers with noise further reduces the breakpoint date beyond the effects of either multiple drivers or noise acting alone (Fig. 4)"; "Our findings also show that 1.2–14.8% of ATDCs can be triggered by additional drivers and/or noise below the threshold of driver strengths required to collapse the system if only a single driver were in effect.").

[400] Kaufhold C., Willeit M., Talento S., Ganopolski A., & Rockström J. (2025) *Interplay between climate and carbon cycle feedbacks could substantially enhance future warming*, ENVIRON. RES. LETT. 20(4): 1–13, 2, 8 ("As only a few ESMs have the ability to simulate CH4 interactively, the long-term impacts of potentially significant carbon cycle feedbacks from permafrost or wetlands have not been accounted for."; "High climate sensitivity (ECS = 5 °C) is responsible for an additional 0.7 °C, 1.0 °C and 1.3 °C by the end of the millennium compared to the reference run for the SSP1-2.6, SSP4-3.4, and SSP2-4.5 scenarios. Carbon cycle feedbacks additionally increases this temperature by 0.6 °C, 0.7 °C and 1.3 °C (figures 4(a)–(c)). In simulations with a low ECS, however, the effect of carbon cycle feedbacks is not as strong, and the majority of temperature changes come from changes in climate sensitivity.").

[401] Drijfhout S., Bathiany S., Beaulieu C., Brovkin V., Claussen M., Huntingford C., Scheffer M., Sgubin G., & Swingedouw D. (2015) *Catalogue of abrupt shifts in Intergovernmental Panel on Climate Change climate models*, PROC. NAT'L. ACAD. SCI. 112(43): E5777–E5786, E5784 ("Permafrost carbon release (51) and methane hydrates release (52) were not expected in CMIP5 simulations, because of missing biogeochemical components in those models capable of simulating such changes."). See also Bathiany S., Hidding J., & Scheffer M. (2020) *Edge Detection Reveals Abrupt and Extreme Climate Events*, J. CLIM. 33(15): 6399–6421, 6416 ("Despite their societal relevance, our knowledge about the risks of future abrupt climate shifts is far from robust. Several important aspects are highly uncertain: future greenhouse gas emissions (scenario uncertainty), the current climate state (initial condition uncertainty), the question whether and how to model specific processes (structural uncertainty), and what values one should choose for parameters appearing in the equations (parametric uncertainty). Such uncertainties can be explored using ensemble simulations. For example, by running many simulations with different combinations of parameter values a perturbed-physics ensemble can address how parameter uncertainty affects the occurrence of extreme events (Clark et al. 2006). This strategy can be particularly beneficial for studying abrupt events as well since abrupt shifts are associated with region-specific processes, whereas models are usually calibrated to produce a realistic global mean climate at the expense of regional realism (Mauritsen et al. 2012; McNeall et al. 2016). The currently available model configurations are therefore neither reliable nor sufficient to assess the risk of abrupt shifts (Drijfhout et al. 2015). It is hence very plausible that yet-undiscovered tipping points can occur in climate models."); Canadell J. G., et al. (2021) *Chapter 5: Global Carbon and other Biogeochemical Cycles and Feedbacks*, in CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Masson-Delmotte V., et al. (eds.), 5-78 ("There is low confidence in the estimate of the non-CO_2 biogeochemical feedbacks, due to the large range in the estimates of α for some individual feedbacks (Figure 5.29c), which can be attributed to the diversity in how models account for these feedbacks, limited process-level understanding, and the existence of known feedbacks for which there is not sufficient evidence to assess the feedback strength."); and Permafrost Pathways, *Course of Action: Mitigation Policy*, Woodwell Climate Research Center (last visited 14 February 2023) ("Depending on how hot we let it get, carbon emissions from Arctic permafrost thaw are expected to be in the range of 30 to more than 150 billion tons of carbon (110 to more than 550 Gt CO_2) this century, with upper estimates on par with the cumulative emissions from the entire United States at its current rate. To put it another way, permafrost thaw emissions could use up between 25 and 40 percent of the remaining carbon budget that would be necessary to cap warming at the internationally agreed-upon 2 degrees Celsius global temperature threshold established in the Paris Agreement. … Despite the enormity of this problem, gaps in permafrost carbon monitoring and modeling are resulting in permafrost being left out of global climate policies, rendering our emissions targets fundamentally inaccurate. World leaders are in a race against time to reduce emissions and prevent Earth's temperature from reaching dangerous levels. The problem is, without including current and projected emissions from permafrost, this race will be impossible to finish. … 82% [o]f IPCC models do not include carbon emissions from permafrost thaw.").

[402] Molina M., Ramanathan V., & Zaelke D. (2018) *Climate report understates threat*, BULLETIN OF THE ATOMIC SCIENTISTS ("These cascading feedbacks include the loss of the Arctic's sea ice, which could disappear entirely in summer in the next 15 years. The ice serves as a shield, reflecting heat back into the atmosphere, but is increasingly

being melted into water that absorbs heat instead. Losing the ice would tremendously increase the Arctic's warming, which is already at least twice the global average rate. This, in turn, would accelerate the collapse of permafrost, releasing its ancient stores of methane, a super climate pollutant 30 times more potent in causing warming than carbon dioxide."). *See also* Ripple W. J., Wolf C., Gregg J. W., Rockström J., Mann M. E., Oreskes N., Lenton T. M., Rahmstorf S., Newsome T. M., Xu C., Svenning J.-C., Pereira C. C., Law B. E., & Crowther T. W. (2024) *The 2024 state of the climate report: Perilous times on planet Earth*, BIOSCI.: 1–13, 9 ("At least 28 amplifying feedback loops have been identified (tables 2a, 2b). A particularly concerning feedback loop is the permafrost feedback loop, which involves rising temperatures causing permafrost thawing. This process releases more carbon dioxide and methane, leading to further warming. … Because feedback loops are not yet fully integrated into climate models, current emissions reduction plans might fall short in adequately limiting future warming. Some climate feedback loops are linked to tipping points, potentially triggering major and irreversible changes in the Earth system without further pushing by human activities.").

[403] Arias P. A., *et al.* (2021) *Technical Summary*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), TS-59 ("The net effect of changes in clouds in response to global warming is to amplify human-induced warming, that is, the net cloud feedback is positive (*high confidence*).") *See also* Ceppi P. & Nowack P. (2021) *Observational evidence that cloud feedback amplifies global warming*, PROC. NAT'L. ACAD. SCI. 118(30): 1–7, 1, 4 ("Global warming drives changes in Earth's cloud cover, which, in turn, may amplify or dampen climate change. This "cloud feedback" is the single most important cause of uncertainty in Equilibrium Climate Sensitivity (ECS)—the equilibrium global warming following a doubling of atmospheric carbon dioxide. Using data from Earth observations and climate model simulations, we here develop a statistical learning analysis of how clouds respond to changes in the environment. We show that global cloud feedback is dominated by the sensitivity of clouds to surface temperature and tropospheric stability. Considering changes in just these two factors, we are able to constrain global cloud feedback to $0.43 \pm 0.35\ W{\cdot}m^{-2}{\cdot}K^{-1}$ (90% confidence), implying a robustly amplifying effect of clouds on global warming and only a 0.5% chance of ECS below 2 K. … Our global constraint implies that a globally positive cloud feedback is virtually certain, thus strengthening prior theoretical and modeling evidence that clouds will provide a moderate amplifying feedback on global warming through a combination of [terrestrial] LW [longwave] and [solar] SW [shortwave] changes. This positive cloud feedback renders ECS lower than 2 K extremely unlikely, confirming scientific understanding that sustained greenhouse gas emissions will cause substantial future warming and potentially dangerous climate change."), *discussed in* Berwyn B. (19 July 2021) *Climate-Driven Changes in Clouds are Likely to Amplify Global Warming*, INSIDE CLIMATE NEWS ("New research, using machine learning, helps project how the buildup of greenhouse gases will change clouds in ways that further heat the planet.").

[404] Schneider T., Kaul C. M., & Pressel K. G. (2019) *Possible climate transitions from breakup of stratocumulus decks under greenhouse warming*, NAT. GEOSCI. 12(3): 163–167, 1, 164 ("In the simulations, stratocumulus decks become unstable and break up into scattered clouds when CO_2 levels rise above 1,200 ppm. In addition to the warming from rising CO_2 levels, this instability triggers a surface warming of about 8 K globally and 10 K in the subtropics. … The subtropical SST jumps by 10 K and the tropical SST by 8 K across the stratocumulus instability (Fig. 3c,d). The tropical warming is a plausible estimate of the global-mean warming triggered by the instability. Subtropical marine stratocumulus clouds cover about 6.5% of the Earth's surface and, where they occur, reduce the solar radiative energy flux absorbed in the climate system by ~110 W m^{-2}, compared to about a 10 W m^{-2} reduction by scattered cumulus[22,28]. If we assume a climate sensitivity parameter of 1.2 K $(W\ m^{-2})^{-1}$ (as for the more sensitive among current GCMs27), this implies $(110 - 10)\ W\ m^{-2} \times 6.5\% \times 1.2\ K\ (W\ m^{-2})^{-1} \approx 8$ K global-mean surface warming when subtropical marine stratocumulus break up.").

[405] Rockström J., *et al.* (2024) *The planetary commons: A new paradigm for safeguarding Earth-regulating systems in the Anthropocene*, PROC. NAT'L. ACAD. SCI. 121(5): 1–10, 3 ("The tipping cascades could accelerate short-term Earth system impacts such as fires, droughts, and floods and undermine planetary resilience in the long term (6, 48, 49). Crossing the tipping points will not only have environmental implications as their structure and functioning change (e.g., from stable to erratic regional rainfall) but is also likely to disrupt socio-economic and political systems that have developed with and are reliant on the stability of the Holocene (23). For instance, around 400 million people

would directly suffer from a demise of tropical corals (51), and at 3 °C of global warming, over three billion people would be living in regions with health-threatening levels of heat (52).”).

[406] Ripple W. J., Wolf C., Gregg J. W., Rockström J., Mann M. E., Oreskes N., Lenton T. M., Rahmstorf S., Newsome T. M., Xu C., Svenning J.-C., Pereira C. C., Law B. E., & Crowther T. W. (2024) *The 2024 state of the climate report: Perilous times on planet Earth*, BIOSCI.: 1–13, 9–10 (“As pressures increase and the risk of Earth’s climate system switching to a catastrophic state rises (Steffen et al. 2018), more and more scientists have begun to research the possibility of societal collapse (Brozovi ́ c 2023). Even in the absence of global collapse, climate change could cause many millions of additional deaths by 2050 (WHO 2023). Along with the broader danger of overshoot, climate change could contribute to a collapse by increasing the likelihood of catastrophic risks such as international conflict or by causing multiple stresses, resulting in system-wide synchronous failures (Kemp et al. 2022). The number of published articles using climate change and societal collapse language has been dramatically increasing (figure 5f; supplemental methods). Climate change has already displaced millions of people, and has the potential to displace hundreds of millions or even billions more, leading to greater geopolitical instability (Table S3).”).

[407] Kemp L., Xu C., Depledge J., Ebi K. L., Gibbins G., Kohler T. A., Rockström J., Scheffer M., Schellnhuber H. J., Steffen W., & Lenton T. M. (2022) *Climate Endgame: Exploring catastrophic climate change scenarios*, PROC. NAT’L. ACAD. SCI. 119(34): 1–9, 3 (“Third, climate change could exacerbate vulnerabilities and cause multiple, indirect stresses (such as economic damage, loss of land, and water and food insecurity) that coalesce into system-wide synchronous failures. This is the path of systemic risk. Global crises tend to occur through such reinforcing “synchronous failures” that spread across countries and systems, as with the 2007–2008 global financial crisis (44). It is plausible that a sudden shift in climate could trigger systems failures that unravel societies across the globe. The potential of systemic climate risk is marked: The most vulnerable states and communities will continue to be the hardest hit in a warming world, exacerbating inequities. Fig. 1 shows how projected population density intersects with extreme >29 °C mean annual temperature (MAT) (such temperatures are currently restricted to only 0.8% of Earth’sland surface area). Using the medium-high scenario of emissions and population growth (SSP3-7.0 emissions, and SSP3 population growth), by 2070, around 2 billion people are expected to live in these extremely hot areas. Currently, only 30 million people live in hot places, primarily in the Sahara Desert and Gulf Coast (43). Extreme temperatures combined with high humidity can negatively affect outdoor worker productivity and yields of major cereal crops. These deadly heat conditions could significantly affect populated areas in South and southwest Asia(47). Fig. 2 takes a political lens on extreme heat, overlapping SSP3-7.0 or SSP5-8.5 projections of >29 °C MAT circa 2070, with the Fragile States Index (a measurement of the instability of states). There is a striking overlap between currently vulnerable states and future areas of extreme warming. If current political fragility does not improve significantly in the coming decades, then a belt of instability with potentially serious ramifications could occur.”). *See also* Stern N., Stiglitz J., & Taylor C. (2022) *The economics of immense risk, urgent action and radical change: towards new approaches to the economics of climate change*, J. ECON. METHODOL. 29(3): 181–216, 182 (“Moreover, at the core of the standard IAM methodology is an analysis of intertemporal trade-offs; how much the current generation should sacrifice in order for future generations to be spared the devastation of climate change. Rising to the climate challenges does indeed involve deep normative questions, including how different generations’ welfare is to be compared and the rights of future generations. But the world has been much more focused than the IAMs on a different set of issues, the risks of catastrophic consequences. These potentially catastrophic risks are in large measure *assumed* away in the IAMs.”).

[408] Pigot A. L., Merow C., Wilson A., & Trisos C. H. (2023) *Abrupt expansion of climate change risks for species globally*, NAT. ECOL. EVOL.: 1–12, 2, 4–5 (“Third, projected thermal exposure will not occur gradually. Instead, over the coming decades, trends of increasing thermal exposure are characterized by periods of relative stability punctuated by sudden pulses, where large numbers of grid cells across a species’ geographical range are exposed in a narrow window of time, with these pulses occurring at different times for different species (Fig. 1). … An abrupt expansion in the area at risk of thermal exposure is a pervasive pattern across species’ geographical ranges. On average, 57% (mean ± 15% s.d.) of the exposure projected for a species this century will occur in a single decade under SSP2-4.5, with similar levels of abruptness under both higher and lower GHG emission pathways (Fig. 2a). Despite the contrasting physical environments in which species occur, the expansion of thermal exposure risks is projected to occur abruptly for both terrestrial (mean = 58% ± 16% s.d.) and marine species (mean = 51% ± 11% s.d.) across all

studied organism groups, from reptiles to zooplankton, and regardless of whether species are widespread (more than a median range size of 34 grid cells; mean = 58% ± 15% s.d.) or geographically rare (fewer than 34 grid cells; mean = 56% ± 15% s.d.). … Within a species' geographical range, most grid cells have relatively narrow warming tolerances, that is, they currently experience maximum monthly temperatures close to the species' range-wide upper realized thermal limit. On average, 65% of a species' geographical range lies in the hottest half of the realized thermal niche, with 27% of the geographical range concentrated within only 10% of the thermal niche. Similar levels of warm-skewness are observed across the geographical ranges of both terrestrial and marine species (Extended Data Fig. 4). This clustering and skew in grid cell warming tolerances means that even when the climate warms gradually, multiple grid cells across a species geographical range are projected to experience thermal exposure near synchronously. … Because different GHG emission scenarios lead to similarly high rates of warming over the next two decades, thermal exposure expands abruptly (Fig. 2a) and with similar timing (Fig. 2b) irrespective of the future emission pathway (Supplementary Fig. 4). … Comparing the dynamics of exposure across all combinations of climate models and GHG emissions pathways, reveals that the number of species at risk of thermal exposure events of both high magnitude and abruptness increases rapidly with the level of global warming (Fig. 5a). For instance, at 1.5 °C of warming, 15% of species are at risk of experiencing exposure across at least 30% of their existing geographical range in a single decade, but this doubles to 30% of species at 2.5 °C of warming. This increase in risk is continuous, so that every fraction of a degree of warming that can be avoided reduces the number of species passing thermal thresholds leading to abrupt and widespread exposure. These results provide evidence that failure to achieve the Paris Agreement climate goals of limiting global warming 'well below' 2 °C, will substantially increase the risk of sudden biodiversity losses.").

[409] Intergovernmental Panel on Climate Change (2022) *Summary for Policymakers*, *in* CLIMATE CHANGE 2022: IMPACTS, ADAPTATION, AND VULNERABILITY, *Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Pörtner H.-O., Roberts D. C., Tignor M., Poloczanska E. S., Mintenbeck K., Alegría A., Craig M., Langsdorf S., Löschke S., Möller V., Okem A., & Rama B. (eds.), SPM-19–20 ("SPM.B.6 If global warming transiently exceeds 1.5°C in the coming decades or later (overshoot)[37], then many human and natural systems will face additional severe risks, compared to remaining below 1.5°C (*high confidence*). Depending on the magnitude and duration of overshoot, some impacts will cause release of additional greenhouse gases (*medium confidence*) and some will be irreversible, even if global warming is reduced (*high confidence*). (Figure SPM.3) … SPM.B.6.1 While model-based assessments of the impacts of overshoot pathways are limited, observations and current understanding of processes permit assessment of impacts from overshoot. Additional warming, e.g., above 1.5°C during an overshoot period this century, will result in irreversible impacts on certain ecosystems with low resilience, such as polar, mountain, and coastal ecosystems, impacted by ice-sheet, glacier melt, or by accelerating and higher committed sea level rise (*high confidence*).[38] Risks to human systems will increase, including those to infrastructure, low-lying coastal settlements, some ecosystem-based adaptation measures, and associated livelihoods (*high confidence*), cultural and spiritual values (*medium confidence*). Projected impacts are less severe with shorter duration and lower levels of overshoot (*medium confidence*). … SPM.B.6.2 Risk of severe impacts increase with every additional increment of global warming during overshoot (*high confidence*). In high-carbon ecosystems (currently storing 3,000 to 4,000 GtC)[39] such impacts are already observed and are projected to increase with every additional increment of global warming, such as increased wildfires, mass mortality of trees, drying of peatlands, and thawing of permafrost, weakening natural land carbon sinks and increasing releases of greenhouse gases (*medium confidence*). The resulting contribution to a potential amplification of global warming indicates that a return to a given global warming level or below would be more challenging (*medium confidence*)."). *See also* Bustamante M., *et al.* (2023) *Ten New Insights in Climate Science 2023/2024*, GLOB. SUSTAIN.: 1–58, 6 ("Breaching the 1.5°C target over decades would leave a long-lasting legacy on the Earth system, since some aspects of the climate and wider environment will not recover, within human-relevant timescales of decades to a century, to the same state as in a reference scenario without overshoot. This is mainly due to the slow response time of key Earth system components. Surface air temperature and precipitation changes appear largely reversible at the global scale following a decline in atmospheric CO_2, but they exhibit irreversibility at regional scale on a timescale of centuries, posing a greater risk to human and natural systems in regions of irreversibility (Kim et al.,2022; Oh et al., 2022). Further long-term, irreversible changes include sea level rise from ocean thermal expansion and melting of ice sheets and glaciers during overshoot, sea ice loss, changes in the deep sea environment (e.g., oxygen, acidity), and changes in structure and composition of terrestrial ecosystems that affect carbon uptake and losses, including permafrost carbon loss (Bauer et al., 2023; IPCC, 2021: Ch4.6.2.1; IPCC, 2022a: Ch2.5.2.10); Schwinger et al., 2022)."); Reisinger A. & Geden O. (2023) *Temporary*

overshoot: Origins, prospects, and a long path ahead, ONE EARTH 6(12): 1631–1637, 1633–1634 ("We suggest that developing a typology of impacts and risks, and risks avoided, under temporary overshoot would enable a clearer conversation about the benefits of such a decline, whereas most literature to date has focused on rising risks as temperature increases. … A related but more complex reason is that impacts, once manifested, leave behind an altered world that cannot be reversed by declining global warming levels. Human populations experiencing repeated droughts (which may scale with global warming level) will change in intergenerational health conditions as well as economic and institutional structures that increase risks to food security even if the frequency and severity of droughts decrease again. … At best, many human and natural systems will exhibit a significant hysteresis in their recovery after global warming levels decline again, but often they will assume a permanently altered state that is difficult to return to the original condition.").

[410] National Snow & Ice Data Center (15 September 2022) *Arctic Weather and Climate* ("Changes in the Arctic climate are important because the Arctic acts as a refrigerator for the rest of the world—it helps cool the planet. So changes in the Arctic climate could affect the climate in the rest of the world. Changes in the Arctic have effects that cascade through the food chain… Researchers say that the changes in the Arctic are worrisome, because they could lead to feedback effects that lead to further warming. For instance, when the white sea ice melts in summer, areas of dark open water are exposed which can absorb more heat from the sun. That extra heat then helps melt even more ice. The loss of sea ice is known to be one of the drivers of Arctic amplification. Permafrost may also be involved in feedbacks. As permafrost thaws, plants and animals that were frozen in the ground begin to decay. When they decay, they release carbon dioxide and methane back to the atmosphere that can contribute to further warming. The changing vegetation of the Arctic also affects the brightness of the surface, which then influences warming. As the Arctic atmosphere warms, it can hold more water vapor, which is an important greenhouse gas."). *See also* Jansen E., *et al.* (2020) *Past perspectives on the present era of abrupt Arctic climate change*, NAT. CLIM. CHANGE 10: 714–721, 714 ("Annual mean temperature trends over the Arctic during the past 40 years show that over this period, where satellite data are available, major portions have warmed by more than 1 °C per decade (Fig. 1a, red colours and outlined portion; a warming of 4 °C within 40 years is hereafter referred to as 1 °C per decade).").

[411] Drollette Jr. D. (30 August 2019) *What if the Arctic melts, and we lose the great white shield? Interview with environmental policy expert Durwood Zaelke*, BULLETIN OF THE ATOMIC SCIENTISTS (article accessible here); Zaelke D. J. & Bledsoe P. (14 December 2019) *Our Future Depends on the Arctic*, THE NEW YORK TIMES; *and* Molina M. & Zaelke D. (16 October 2020) *The Time Bomb at the Top of the World*, PROJECT SYNDICATE.

[412] Pistone K., Eisenman I., & Ramanathan V. (2014) *Observational determination of albedo decrease caused by vanishing Arctic sea ice*, PROC. NAT'L. ACAD. SCI. 111(9): 3322–3326, 3322 ("As per the Budyko–Sellers hypothesis, an initial warming of the Arctic due to factors such as CO_2 forcing will lead to decreased ice cover which exposes more of the underlying darker ocean and amplifies the warming. In 1975, this phenomenon was simulated in a 3D climate model by Manabe and Wetherald (9), who showed that under conditions of a doubling of CO_2, tropospheric warming in the polar regions was much larger than in the tropics, due in part to the albedo decrease from shrinking snow/ice area.").

[413] Sumata H., de Steur L., Divine D. V., Granskog M. A., & Gerland S. (2023) *Regime shift in Arctic Ocean sea ice thickness*, NATURE, 615(7952): 443–49, 448 ("Thus, summer ice extent and thickness in areas of ice formation has not recovered to the state before 2007 (Fig. 4c). In addition, continuing weakening of the cold halocline in the Siberian sector also influenced the upper ocean heat content46 and possibly slowed down ice growth offshore of the Laptev Sea in recent years. Our analysis demonstrates the long-lasting impact of climate change on Arctic sea ice through reduced residence time, suggesting an irreversible response of Arctic sea ice thickness connected to an increase of ocean heat content in areas of ice formation."), *discussed in* Dance S. (16 March 2023) *Arctic ice has seen an 'irreversible' thinning since 2007, study says*, WASHINGTON POST.

[414] Rantanen M., Karpechko A. Y., Lipponen A., Nordling K., Hyvärinen O., Ruosteenoja K., Vihma T. & Laaksonen A. (2022) *The Arctic has warmed nearly four times faster than the globe since 1979*, COMMUN. EARTH ENVIRON. 3(168): 1–10, 3 ("During 1979–2021, major portions of the Arctic Ocean were warming at least four times as fast as the global average (Fig. 1c). The most extreme AA [Arctic amplification] values occur in the sea areas near Novaya

Zemlya, which were locally warming up to seven times as fast as the global average. … In general, there are no regions within the Arctic Circle where AA[43] is smaller than two, apart from the northern North Atlantic."), *discussed in* Budryk Z. (11 August 2022) *Arctic warming up to four times as fast as global average: study*, THE HILL. One recent study accounted for the influence of natural variability on Arctic amplification and found that approximately 75% of the increasing Arctic rate of warming is due to external (i.e., anthropogenic) forcing; *see* Zhou W., Leung L. R., & Lu J. (2024) *Steady threefold Arctic amplification of externally forced warming masked by natural variability*, NAT. GEOSCI.: 1–10, 6–7 ("For all possible periods longer than 30 years over 1967–2020, removing the effect of IPO [tripole index] on global mean temperature constrains the range of AA from 1.66–4.39 in observations (Fig. 5a) to 1.97–4.06 (Fig. 5b). Further removing the effect of AM on Arctic mean temperature constrains the range of the forced AA to 2.65–3.29 (Fig. 5c). For the periods of 1970–2004 and 1980–2014, the degree of AA is 2.09 and 3.98 in observations (Fig. 5a) but becomes 2.28 and 3.33 after removing the effect of IPO (Fig. 5b) and 2.85 and 2.94 after removing the effects of both IPO and AM (Fig. 5c). Thus, the degree of the externally forced AA, estimated by removing the effect of IPO and AM from observations, is consistently close to three throughout the historical period. … Furthermore, by excluding the effects of IPO and AM from the observed temperature trends, we reveal that the externally forced AA remains close to three throughout the historical period.").

[415] Ballinger T. J., Crawford A., Serreze M. C., Bigaalke S., Walsh J. E., Brettschneider B., Thoman R. L., Bhatt U. S., Hanna E., Motrøen Gjelten H.., Kim S. – J., Overland J. E., & Wang M. (2024) *Surface Air Temperature*, *in* ARCTIC REPORT CARD 2024, Moon T. A., Druckenmiller M. L., & Thoman R. L. (eds.), National Oceanic and Atmospheric Administration, 9 ("This past year was the Arctic's 2nd warmest on record since 1900 with anomalies of 1.20°C above the 1991-2020 mean. While 2024 is on track to be the warmest year on record globally since at least 1900, Arctic temperature anomalies continue to be larger. This is the 11th consecutive year in which Arctic regional temperature departures exceeded those of the Earth as a whole. This past decade has been the Arctic's warmest, and has been characterized by several new annual and seasonal records.").

[416] Meier W. N., Petty A., Hendricks S., Bliss A., Kaleschke L., Divine D., Farrell S., Gerland S., Perovich D., Ricker R., Tian-Kunze X., Webster M. (2024) *Sea Ice*, *in* ARCTIC REPORT CARD 2024, Moon T. A., Druckenmiller M. L., & Thoman R. L. (eds.), National Oceanic and Atmospheric Administration, 41 ("This satellite record tracks long-term trends, variability, and seasonal changes from the annual extent maximum in late February or March to the annual extent minimum in September. In recent years, minimum extents are ~50% of the values in the 1980s. In 2024, March and September extents were similar to other recent years (Fig. 1), but much lower than the 1991-2020 average, and the long-term negative trends continue (Table 1)."). *See also* Arctic Monitoring and Assessment Programme (2021) ARCTIC CLIMATE CHANGE UPDATE 2021: KEY TRENDS AND IMPACTS, Summary for Policymakers, 6 ("The extent of Arctic sea ice in September declined by 43% between 1979 and 2019, and—with the exception of the Bering Sea—sea-ice extent and area are declining throughout the Arctic in all months. Sea-ice cover also continues to be younger and thinner than during the 1980s, 1990s, and early 2000s.").

[417] Note that there is a difference between the *first* occurrence of a sea ice-free Arctic and a *consistently* sea-ice free Arctic. Additionally, different studies use different thresholds to define a sea ice-free month; for a review, *see* Jahn A., Holland M. M., & Kay J. E. (2024) *Projections of an ice-free Arctic Ocean*, NAT. REV. EARTH ENVIRON. 5(3): 164–176, 164 ("In the September monthly mean, the earliest ice-free conditions (the first single occurrence of an ice-free Arctic) could occur in 2020–2030s under all emission trajectories and are likely to occur by 2050. However, daily September ice-free conditions are expected approximately 4 years earlier on average, with the possibility of preceding monthly metrics by 10 years. Consistently ice-free September conditions (frequent occurrences of an ice-free Arctic) are anticipated by mid-century (by 2035–2067), with emission trajectories determining how often and for how long the Arctic could be ice free."). Constraining model projections, by adding in observational data, may provide more reliable estimates of when the Arctic will be sea ice-free in September, but this all depends on whether regional-level trends are considered; *see* Paik S., Kim D., An S.-I., & Ham Y.-G. (2023) *Constraining the First Year of Ice-Free Arctic: Importance of Regional Perspective*, EARTH'S FUTURE 11(10): 1–14, 8–10, 11 ("Projections constrained by the historical September Arctic SIA climatology and trend exhibit an earlier emergence of the first ice-free September in the Arctic (mean = 2038) compared to the unconstrained model simulation projections (mean = 2044), with a reduced uncertainty range. … Alternatively, when constrained using the historical trend of the September central Arctic SIA, the timing of the first ice-free Arctic in September was delayed by over 10 years, with an average estimate

of 2056. This can be primarily attributed to the common overestimation of the magnitude of the observed historical September central Arctic SIA decreasing trend in CMIP6 model simulations."); *compare with* Kim Y.-H., Min S.-K., Gillett N. P., Notz D., & Malinina E. (2023) *Observationally-constrained projections of an ice-free Arctic even under a low emission scenario*, NAT. COMMUN. 14(3139): 1–8, 5 ("Based on the GHG+ scaling factors, we produce observationally-constrained future changes in Arctic SIA under four SSP scenarios. Results indicate that the first sea ice-free September will occur as early as the 2030s–2050s irrespective of emission scenarios. Extended occurrences of an ice-free Arctic in the early summer months are projected later in the century under higher emissions scenarios."). In addition, findings of ice-free September Arctic sea ice may be too early by a decade if models are not properly accounting for larger changes in atmospheric circulation, *according to* Topál D. & Ding Q. (2023) *Atmospheric circulation-constrained model sensitivity recalibrates Arctic climate projections*, NAT. CLIM. CHANG. 1–9, 5 ("To showcase our point, we use the abovementioned method to constrain the timing of the first sea-ice-free September in the SMILEs and CMIP6 models. The cumulative probability density functions (CDFs) corresponding to the time of emergence of the first seasonally sea-ice-free Arctic[52,53] (below 1 million km^2 in September) in the raw and the calibrated SIE time series in the model ensembles show prospects of a 9–11-year delay of the 'likely' (in IPCC[54] terms) probability ($P > 0.66$) of a September ice-free Arctic, such that an ice-free summer before 2050 is 'as likely as not' (in IPCC terms $0.33 < P < 0.66$) (Fig. 5c; Methods). This result is in contrast to estimates from previous studies that project ice-free September as early as mid-century[33]. Our results are also at odds with a recent study, where the authors used Arctic temperatures as an emergent constraint on ice-free projections in CMIP6 (ref. 40)."). *See also* Docquier D. & Koenigk T. (2021) *Observation-based selection of climate models projects Arctic ice-free summers around 2035*, COMMUN. EARTH ENVIRON. 2(144): 1–8; *and* Peng G., Matthews J. L., Wang M., Vose R., & Sun L. (2020) *What Do Global Climate Models Tell Us about Future Arctic Sea Ice Coverage Changes?*, CLIMATE 8(15): 1–24.

[418] Bonan D. B., Schneider T., Eisenman I., & Wills R. C. J. (2021) *Constraining the Date of a Seasonally Ice-Free Arctic Using a Simple Model*, GEOPHYS. RES. LETT. 48(18): 1–12, 1 ("Under a high-emissions scenario, an ice-free Arctic will likely (>66% probability) occur between 2036 and 2056 in September and between 2050 and 2068 from July to October. Under a medium-emissions scenario, the "likely" date occurs between 2040 and 2062 in September and much later in the 21st century from July to October."). In addition, a *consistently* sea ice-free Arctic in September and other months will occur later, than the *first* time the Arctic is sea ice-free for a given month or season; *see* Jahn A., Holland M. M., & Kay J. E. (2024) *Projections of an ice-free Arctic Ocean*, NAT. REV. EARTH ENVIRON. 5(3): 164–176, 171 ("For example, there is a possibility of occasional ice-free conditions in August and October with <2 °C warming (or SSP1-1.9) (refs. 76,85), extending into July with ≥2.5 °C warming[85] (or SSP1-2.6) and into November with ≥3.5 °C warming76 (or SSP2-4.5) (Fig. 4). In some select CMIP6 models under SSP5-8.5, first ice-free conditions also occur in December, January, May and June during the second half of the twenty-first century (Fig. 4d) when warming exceeds 3.5 °C (ref. 114). … For the selected CMIP6 models forced with SSP2-4.5, the ice-free season is expected to span 3 months per year by 2100 (as determined by continuous likely (>66%) ice-free conditions): ice-free conditions emerge in August by approximately 2055 and in October by approximately 2080 (Fig. 4c). In contrast, the likely ice-free season is expected to span 6 months for SSP5-8.5: beyond September, continuous ice-free conditions emerge in August by approximately 2050, in October by approximately 2055, in November by approximately 2070, in July by approximately 2075 and in December by approximately 2090 (ice-free conditions in July to October become very likely or virtually certain by 2100) (Fig. 4d). Consistently ice-free conditions are not expected beyond September for SSP1-1.9 (Fig. 4a) or SSP1-2.6 (Fig. 4b).").

[419] Pistone K., Eisenman I., & Ramanathan V. (2019) *Radiative Heating of an Ice-Free Arctic Ocean*, GEOPHYS. RES. LETT. 46(13): 7474–7480, 7477 ("This heating of 0.71 W/m^2 is approximately equivalent to the direct radiative effect of emitting one trillion tons of CO_2 into the atmosphere (see calculation in Appendix A). As of 2016, an estimated 2.4 trillion tons of CO_2 have been emitted since the preindustrial period due to both fossil fuel combustion (1.54 trillion tons) and land use changes (0.82 trillion tons), with an additional 40 billion tons of CO_2 per year emitted from these sources during 2007–2016 (Le Quéré et al., 2018). Thus, the additional warming due to the complete loss of Arctic sea ice would be equivalent to 25 years of global CO_2 emissions at the current rate."). *See also* Institute for Governance & Sustainable Development (2019) *Plain Language Summary of Pistone K., et al*.

[420] Wadhams P. (2017) [A FAREWELL TO ICE: A REPORT FROM THE ARCTIC], Oxford University Press, 107–108 ("Warm air over an ice-free Arctic also causes the snowline to retreat. … This of the same magnitude as the sea ice negative anomaly during the same period, and the change in albedo is roughly the same between snow-covered land and snow-free tundra as it is between sea ice and open water. Nobody has yet published the calculations for tundra as Pistone and her colleagues did for sea ice, but the similarity of the magnitudes means that snowline retreat and sea ice retreat are each adding about the same amount to global warming.").

[421] Wang Q., Wekerle C., Wang X., Danilov S., Koldunov N., Sein D., Sidorenko D., von Appen W.-J., & Jung T. (2020) *Intensification of the Atlantic Water Supply to the Arctic Ocean Through Fram Strait Induced by Arctic Sea Ice Decline*, GEOPHYS. RES. LETT. 47(3): 1–10, 1, 8 ("The reduction in sea ice export through Fram Strait induced by Arctic sea ice decline increases the salinity in the Greenland Sea, which lowers the sea surface height and strengthens the cyclonic gyre circulation in the Nordic Seas. The Atlantic Water volume transport to the Nordic Seas and Arctic Ocean is consequently strengthened. This enhances the warming trend of the Arctic Atlantic Water layer, potentially contributing to the Arctic "Atlantification." … In these processes, the Nordic Seas play the role of a switchyard, while the reduction of sea ice export flux caused by increased air-sea heat flux over the Arctic Ocean is the switchgear. Increasing ocean heat can reduce sea ice thickness, and currently this occurs mainly in certain regions including the western Eurasian Basin near the Fram Strait and the northern Kara Sea (Carmack et al., 2015; Dmitrenko et al., 2014; Ivanov et al., 2012; Onarheim et al., 2014; Polyakov et al., 2010).").

[422] MacKinnon J. A., *et al.* (2021) *A warm jet in a cold ocean*, NAT. COMMUN. 12(2418): 1–12, 1 ("Unprecedented quantities of heat are entering the Pacific sector of the Arctic Ocean through Bering Strait, particularly during summer months. Though some heat is lost to the atmosphere during autumn cooling, a significant fraction of the incoming warm, salty water subducts (dives beneath) below a cooler fresher layer of near-surface water, subsequently extending hundreds of kilometers into the Beaufort Gyre. Upward turbulent mixing of these sub-surface pockets of heat is likely accelerating sea ice melt in the region. This Pacific-origin water brings both heat and unique biogeochemical properties, contributing to a changing Arctic ecosystem.").

[423] Zhang J., Lindsay R., Schweiger A., & Steele M. (2013) *The impact of an intense summer cyclone on 2012 Arctic sea ice retreat*, GEOPHYS. RES. LETT. 40(4): 720–726, 722 ("The rapid reduction in ice volume during the storm is due to enhanced ice melt (Figures 3a–3d). The simulated total ice melt is 0.12×10^3 km^3 d^{-1} before the cyclone, but almost doubled during the cyclone, averaging 0.21×10^3 km^3 d^{-1} (or 0.17×10^3 km^3 d^{-1} in the ICAPS) during 6–8 August (Figure 2c and Table 1). The enhanced melt is widespread in the ICAPS, but is strongest in the Canada Basin, where ice melt is as high as 0.12 m d^{-1} (Figures 3b and 3c). This explains the large decrease in ice thickness during the storm in these areas (Figures 1j–1l), up to 0.5 m by 10 August (Figure 1l). The simulated ice in most of these areas was already thin on 4 August before the storm (Figures 1i and 2b)."). *See also* Valkonen E., Cassano J., & Cassano E. (2021) *Arctic Cyclones and their Interactions With the Declining Sea Ice: A Recent Climatology*, J. GEOPHYS. RES. ATMOS. 126(12): 1–35, 20–21 ("We also showed that the increased cyclone counts in the cold season were indeed connected to the declining sea ice in both the warm and cold seasons (Figures 11and A15). Less sea ice in the cold season or the following warm season was related to increased cyclone counts in the cold season."); Finocchio P. M. & Doyle J. D. (2022) *Summer Cyclones and Their Association With Short-Term Sea Ice Variability in the Pacific Sector of the Arctic*, FRONT. EARTH SCI. 9(738497): 1–17, 15 ("The advective tendency of SIC due to the 10-m wind is one of the most consistent predictors of both local and regional ice loss for the large sample of cyclones in the ECB region. We find the strongest relationship between advection and sea ice loss for low concentration sea ice in August. This supports previous studies arguing that the reduced mechanical strength of lower concentration sea ice makes it more susceptible to wind-induced drift and deformation (Hakkinen et al., 2008; Rampal et al., 2009; Spreen et al., 2011)."); *and* Finocchio P. M., Doyle J. D., & Stern D. P. (2022) *Accelerated Sea Ice Loss from Late Summer Cyclones in the New Arctic*, J. CLIM. 35(23): 4151–4169, 4151 ("We compare the 1–7-day changes in sea ice area and thickness following days in each month with and without cyclones from two decades: 1991–2000 and 2009–18. Only in August do cyclones locally accelerate seasonal sea ice loss on average, and the ability of August cyclones to accelerate ice loss has become more pronounced in the recent decade. The recent increase in ice loss following August cyclones is most evident in the Amerasian Arctic (140°E–120°W), where reanalyses indicate that the average upper-ocean temperature has increased by 0.2°–0.8°C and the average ice thickness has decreased by almost 1 m between the two decades. Such changes promote cyclone-induced ocean mixing and sea ice divergence that locally increase the

likelihood for rapid ice loss near cyclones. In contrast, June cyclones in both decades locally slow down seasonal sea ice loss. Moreover, the 7-day sea ice loss in June has increased from the early to the recent decade by 67% more in the absence of cyclones than in the presence of cyclones. The largest increases in June ice loss occur in the Eurasian Arctic (0°–140°E), where substantial reductions in average surface albedo in the recent decade have allowed more of the abundant insolation in the absence of cyclones to be absorbed at the sea surface."). Research is also underway that analyzes 2022 trends for accelerated ice loss in the Arctic due to late summer cyclones: *see* Hand E. (23 August 2022) *Arctic stormchasers brave giant cyclones to understand how they chew up sea ice*, SCIENCE.

[424] Rantanen M., Karpechko A. Y., Lipponen A., Nordling K., Hyvärinen O., Ruosteenoja K., Vihma T. & Laaksonen A. (2022) *The Arctic has warmed nearly four times faster than the globe since 1979*, COMMUN. EARTH ENVIRON. 3(168): 1–10, 3 ("During 1979–2021, major portions of the Arctic Ocean were warming at least four times as fast as the global average (Fig. 1c). The most extreme AA [Arctic amplification] values occur in the sea areas near Novaya Zemlya, which were locally warming up to seven times as fast as the global average. … In general, there are no regions within the Arctic Circle where AA[43] is smaller than two, apart from the northern North Atlantic."), *discussed in* Budryk Z. (11 August 2022) *Arctic warming up to four times as fast as global average: study*, THE HILL. One recent study accounted for the influence of natural variability on Arctic amplification and found that approximately 75% of the increasing Arctic rate of warming is due to external (i.e., anthropogenic) forcing; *see* Zhou W., Leung L. R., & Lu J. (2024) *Steady threefold Arctic amplification of externally forced warming masked by natural variability*, NAT. GEOSCI.: 1–10, 6–7 ("For all possible periods longer than 30 years over 1967–2020, removing the effect of IPO [tripole index] on global mean temperature constrains the range of AA from 1.66–4.39 in observations (Fig. 5a) to 1.97–4.06 (Fig. 5b). Further removing the effect of AM on Arctic mean temperature constrains the range of the forced AA to 2.65–3.29 (Fig. 5c). For the periods of 1970–2004 and 1980–2014, the degree of AA is 2.09 and 3.98 in observations (Fig. 5a) but becomes 2.28 and 3.33 after removing the effect of IPO (Fig. 5b) and 2.85 and 2.94 after removing the effects of both IPO and AM (Fig. 5c). Thus, the degree of the externally forced AA, estimated by removing the effect of IPO and AM from observations, is consistently close to three throughout the historical period. … Furthermore, by excluding the effects of IPO and AM from the observed temperature trends, we reveal that the externally forced AA remains close to three throughout the historical period.").

[425] Cai Z., You Q., Wu F., Chen H., Chen D., & Cohen J. (2021) *Arctic Warming Revealed by Multiple CMIP6 Models: Evaluation of Historical Simulations and Quantification of Future Projection Uncertainties*, J. CLIM. 34(12): 4871–4892, 4878 ("The Arctic's warming rate from 1986 to 2100 is much higher than that of the Northern Hemisphere and the global mean under the three different scenarios (You et al. 2021). Figure 8 shows the spatial patterns of annual mean near-surface temperature change in the Arctic according to the MMEM [multi-model ensemble mean] for the three periods relative to 1986–2005 under the three scenarios. Projections for the regionally averaged mean near-surface temperature increases in the Arctic under SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios are +2.5°, +2.6°, and +2.8°C respectively in the near term (2021–40), +3.3°, +4.0°, and +5.1°C in the midterm (2014–60), and +3.5°, +5.8°, and +10.4°C in the long-term (2081–2100) relative to the reference period based on the CMIP6 MMEM.").

[426] Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, REV. GEOPHYS. 61: 1–81, 26 ("The accelerated pace of boreal climatic shifts relative to the rest of the world is likely to continue over the 21st century. Warming of 3–5°C globally by end-of-century would imply average temperature increases of 7–10°C for large parts of Russia, with regional warming of up to 12°C (Schaphoff et al., 2016).").

[428] Schweiger A. J., Steele M., Zhang J., Moore G. W. K., & Laidre K. L. (2021) *Accelerated sea ice loss in the Wandel Sea points to a change in the Arctic's Last Ice Area*, COMMUN. EARTH ENVIRON. 2(122): 1–11, 2, 5–6 ("The Polarstern's route was guided by satellite images showing extensive areas of open water and sea ice concentration (SIC) as low as 70% at 87N (Figs. 1a, S1b). We define our WS [Wandel Sea] study area by 81.5°N–85°N, 10°W–50°W, the same area where we saw signs of change in February 201810. Daily 2020 WS SIC drops below the 5th percentile of the 1979–2020 time series on July 25 and stays there almost until the end of August (Fig. 1b). August 14, 2020 constitutes a record low 52% SIC minimum (Fig. 1c). Several earlier years (e.g., 1985: 57%, 1990: 67%, and 1991: 62%) also show significant low SIC minima, although none as low as 2020."); 1 ("During spring 2020, ice accumulated in the WS (Fig. 4a, b) in response to anomalous advection (mostly in February; Fig. 4c, d). As a result,

ice thickness was near its 1979–2020 mean value by June 1 according to PIOMAS; Fig. 2c), and actually thicker than in recent years (2011–2019) as confirmed by the combined CryoSat-2/SMOS satellite product… While primarily driven by unusual weather, climate change in the form of thinning sea ice contributed significantly to the record low August 2020 SIC in the WS. Several advection events, some relatively early in the melt season, transported sea ice out of the region and allowed the accumulation of heat from the absorption of solar radiation in the ocean. This heat was mixed upward and contributed to rapid melt during high wind events, notably between August 9 and 16. Ocean-forced melting in this area that is traditionally covered by thick, compact ice is a key finding of this study. … These ensemble experiments underline the importance of both spring sea ice and summer atmospheric forcing to August SIC. In summary, we find that: Spring ice conditions were mostly responsible for the summer SIC anomaly through the end of July, while the atmosphere was mainly responsible for driving SIC to a record low during August. Partitioning the impact of 2020 spring initial sea ice conditions vs. summer atmospheric forcing on the sea ice anomaly at the time of the WS sea ice minimum on August 14 (see "Methods") attributes ~20% to the initial conditions while ~80% is the due to the atmospheric forcing.").

[429] Labe Z., Magnusdottir G., & Stern H. (2018) *Variability of Arctic Sea Ice Thickness Using PIOMAS and the CESM Large Ensemble,* J. CLIM. 31(8): 3233–3247, 3243 (Figure 10. "While twenty-first-century sea ice thins substantially in all seasons, a large sea ice cover continues to reform during the cold season. A region of perennially thick ice north of Greenland also remains…. An area of perennially thick sea ice remains north of Greenland during all months of the year, but it significantly thins (especially in September) by the mid-twenty-first century. Average September SIT [sea ice thickness] in all regions eventually falls below 0.5 m during the 21st century.").

[430] Schweiger A. J., Steele M., Zhang J., Moore G. W. K., & Laidre K. L. (2021) *Accelerated sea ice loss in the Wandel Sea points to a change in the Arctic's Last Ice Area*, COMMUN. EARTH ENVIRON. 2(122): 1–11, 2 ("The LIA is considered to be a last refuge for ice-associated Arctic marine mammals, such as polar bears (*Ursus maritimus*), ice-dependent seals such as ringed seals (*Pusa hispida*) and bearded seals (*Erignathus barbatus*), and walrus (*Odobendus rosmarus*) throughout the 21st century.").

[431] Isaksen K., *et al.* (2022) *Exceptional warming over the Barents sea*, SCI. REP. 12(9371): 1–18, 11 ("The accelerated warming up to the latest decade is in agreement with the most recent assessments of instrumental observations in the Arctic[7,8]. Przybylak and Wyszyński[8] analyzed trends from 1951 to 2015 and showed that the strongest temperature increase in the Arctic in winter was observed over Svalbard, but no stations in north-eastern areas were then available. By including newly available SAT [surface air temperature] observations from northern and eastern Svalbard and from FJL [Svalbard and Franz Josef Land], we were able to additionally study the regional SAT developments in the NBS [Northern Barents Sea]. Our main findings are summarised in Fig. 7 and show that the warming in western Svalbard is large, but even larger in northern and eastern Svalbard and in FJL. From 1981 to 2020, we found an annual warming rate varying between 1.0 and 1.6 °C per decade, whereas, over the two periods 1991–2020 and 2001–2020, the annual warming rates ranged from 1.1 to 2.7 °C per decade. These rates are stronger than hitherto known in this region. The increasing temperature rates for the Northern Barents Sea region are exceptional on the Arctic and global scale and correspond to 2 to 2.5 times the Arctic warming averages and 5 to 7 times the global warming averages (Fig. 7)."), *discussed in* Carrington D. (15 June 2022) *New data reveals extraordinary global heating in the Arctic*, THE GUARDIAN.

[432] Isaksen K., *et al.* (2022) *Exceptional warming over the Barents sea*, SCI. REP. 12(9371): 1–18, 3 ("Record-high warming was observed over the two periods 1991–2020 and 2001–2020, with annual values ranging from ~ 1.1 °C per decade in Ny-Ålesund to 2.7 °C per decade at Karl XII-øya (Table 1 and Fig. 3c). The annual warming was dominated by higher autumn and winter warming but enhanced warming occurred in all seasons (Table 1). In autumn (SON) we noticed an accelerated warming for 1991–2020 and 2001–2020, with up to 4.0 °C per decade for the latter period at Karl XII-øya."), *discussed in* Carrington D. (15 June 2022) *New data reveals extraordinary global heating in the Arctic*, THE GUARDIAN.

[433] Timmermans M. -L. & Labe Z. (2023) *Sea Surface Temperature*, *in* ARCTIC REPORT CARD 2023, Thoman R. L., Moon T. A., & Druckenmiller M. L. (eds.), National Oceanic and Atmospheric Administration, 51 ("The Arctic Ocean has experienced mean August SST warming trends from 1982 to 2023, with statistically significant (at the 95%

confidence interval) linear warming trends in almost all regions (Fig. 3a). Mean August SSTs for the Arctic Ocean and marginal seas between 65° N and 80° N exhibit a linear warming trend of 0.05 ± 0.01°C/year (Fig. 3b; SSTs for 80° N-90° N are omitted since this region is largely perennially ice covered).").

434 International Cryosphere Climate Initiative (2023) STATE OF THE CRYOSPHERE REPORT 2023 – TWO DEGREES IS TOO HIGH, 41 ("This former "ecosystem of ice" no longer exists. … The occurrence of the first sea ice-free Arctic summer is therefore unpredictable, but scientists now believe it is inevitable, and likely to occur at least once before 2050 even under a "very low" emissions scenario.[13,27,28,30] … In contrast, continuing on the current emissions trajectory may lead to the Arctic becoming ice free in the summer as soon as the 2030s.23 Even moderate emissions will lead to ice-free conditions most summers once global mean temperature rise reaches about 1.7°C. The length of this ice-free state would increase in lock-step with emissions and temperature,[10,28,29,39] eventually stretching from July–October at 2°C.[21,29]").

435 Meier W. N., Petty A., Hendricks S., Bliss A., Kaleschke L., Divine D., Farrell S., Gerland S., Perovich D., Ricker R., Tian-Kunze X., Webster M. (2024) *Sea Ice*, ***in*** ARCTIC REPORT CARD 2024, Moon T. A., Druckenmiller M. L., & Thoman R. L. (eds.), National Oceanic and Atmospheric Administration, 41 ("This satellite record tracks long-term trends, variability, and seasonal changes from the annual extent maximum in late February or March to the annual extent minimum in September. In recent years, minimum extents are ~50% of the values in the 1980s. In 2024, March and September extents were similar to other recent years (Fig. 1), but much lower than the 1991-2020 average, and the long-term negative trends continue (Table 1).").

436 Note that there is a difference between the *first* occurrence of a sea ice-free Arctic and a *consistently* sea-ice free Arctic. Additionally, different studies use different thresholds to define a sea ice-free month; for a review, *see* Jahn A., Holland M. M., & Kay J. E. (2024) *Projections of an ice-free Arctic Ocean*, NAT. REV. EARTH ENVIRON. 5(3): 164–176, 164 ("In the September monthly mean, the earliest ice-free conditions (the first single occurrence of an ice-free Arctic) could occur in 2020–2030s under all emission trajectories and are likely to occur by 2050. However, daily September ice-free conditions are expected approximately 4 years earlier on average, with the possibility of preceding monthly metrics by 10 years. Consistently ice-free September conditions (frequent occurrences of an ice-free Arctic) are anticipated by mid-century (by 2035–2067), with emission trajectories determining how often and for how long the Arctic could be ice free."). Constraining model projections, by adding in observational data, may provide more reliable estimates of when the Arctic will be sea ice-free in September, but this all depends on whether regional-level trends are considered; *see* Paik S., Kim D., An S.-I., & Ham Y.-G. (2023) *Constraining the First Year of Ice-Free Arctic: Importance of Regional Perspective*, EARTH'S FUTURE 11(10): 1–14, 8–10, 11 ("Projections constrained by the historical September Arctic SIA climatology and trend exhibit an earlier emergence of the first ice-free September in the Arctic (mean = 2038) compared to the unconstrained model simulation projections (mean = 2044), with a reduced uncertainty range. … Alternatively, when constrained using the historical trend of the September central Arctic SIA, the timing of the first ice-free Arctic in September was delayed by over 10 years, with an average estimate of 2056. This can be primarily attributed to the common overestimation of the magnitude of the observed historical September central Arctic SIA decreasing trend in CMIP6 model simulations."; "When the projections are constrained using the observed historical September SIA climatology and trend across the entire Arctic, the first ice-free September in the Arctic, may emerge at a slightly earlier compared to the unconstrained projections, while simultaneously reducing uncertainty ranges. In contrast, when constraints are based on the historical September SIA trend over the central Arctic, there was a significant delay in the projection for the first ice-free September in the Arctic. These contrasting results demonstrate the significance of considering regional changes, compared to focusing solely on the Arctic as a whole."). *Compare with* Kim Y.-H., Min S.-K., Gillett N. P., Notz D., & Malinina E. (2023) *Observationally-constrained projections of an ice-free Arctic even under a low emission scenario*, NAT. COMMUN. 14(3139): 1–8, 5 ("Based on the GHG+ scaling factors, we produce observationally-constrained future changes in Arctic SIA under four SSP scenarios. Results indicate that the first sea ice-free September will occur as early as the 2030s–2050s irrespective of emission scenarios. Extended occurrences of an ice-free Arctic in the early summer months are projected later in the century under higher emissions scenarios."). In addition, findings of ice-free September Arctic sea ice may be too early by a decade if models are not properly accounting for larger changes in atmospheric circulation, *according to* Topál D. & Ding Q. (2023) *Atmospheric circulation-constrained model sensitivity recalibrates Arctic climate projections*, NAT. CLIM. CHANG. 1–9, 5 ("To showcase our point, we use the

abovementioned method to constrain the timing of the first sea-ice-free September in the SMILEs and CMIP6 models. The cumulative probability density functions (CDFs) corresponding to the time of emergence of the first seasonally sea-ice-free Arctic[52,53] (below 1 million km^2 in September) in the raw and the calibrated SIE time series in the model ensembles show prospects of a 9–11-year delay of the 'likely' (in IPCC[54] terms) probability ($P > 0.66$) of a September ice-free Arctic, such that an ice-free summer before 2050 is 'as likely as not' (in IPCC terms $0.33 < P < 0.66$) (Fig. 5c; Methods). This result is in contrast to estimates from previous studies that project ice-free September as early as mid-century[33]. Our results are also at odds with a recent study, where the authors used Arctic temperatures as an emergent constraint on ice-free projections in CMIP6 (ref. 40)."). *See also* Docquier D. & Koenigk T. (2021) *Observation-based selection of climate models projects Arctic ice-free summers around 2035*, COMMUN. EARTH ENVIRON. 2(144): 1–8; *and* Peng G., Matthews J. L., Wang M., Vose R., & Sun L. (2020) *What Do Global Climate Models Tell Us about Future Arctic Sea Ice Coverage Changes?*, CLIMATE 8(15): 1–24.

437 Pistone K., Eisenman I., & Ramanathan V. (2019) *Radiative Heating of an Ice-Free Arctic Ocean*, GEOPHYS. RES. LETT. 46(13): 7474–7480, 7474 ("Here we use satellite observations to estimate the amount of solar energy that would be added in the worst-case scenario of a complete disappearance of Arctic sea ice throughout the sunlit part of the year. Assuming constant cloudiness, we calculate a global radiative heating of 0.71 W/m^2 relative to the 1979 baseline state. This is equivalent to the effect of one trillion tons of CO_2 emissions. These results suggest that the additional heating due to complete Arctic sea ice loss would hasten global warming by an estimated 25 years.").

438 National Snow & Ice Data Center (3 October 2024) *The new abnormal* ("Including 2024, the downward linear trend in Arctic sea ice extent for September is 78,000 square kilometers (30,000 square miles) per year, or 12.13 percent per decade relative to the 1981 to 2010 average. Based on the linear trend, since 1979, September has lost 1.61 million square kilometers (622,000 square miles) of sea ice, which is roughly equivalent to the state of Alaska or the country of Iran.").

439 Wang X., Liu Y., Key J. R., & Dworak R. (2022) *A New Perspective on Four Decades of Changes in Arctic Sea Ice from Satellite Observations*, REMOTE SENS. 14(8): 1846, 1–22, 19–20 ("Arctic AICA [an ice-covered area] SIE [sea ice extent] was reduced 22% over the last four decades, mainly caused by PICA [perennial ice-covered area] SIE reduction that declined at an annual rate of −1.105 × 105 km^2 per year. The annual increase in SICA [seasonal ice-covered area] SIE, at a rate of 2.640 × 104 km^2 per year, does not offset the decline in the PICA SIE, resulting in a net loss of AICA SIE at a rate of −7.871 × 104 km^2 per year. The AICA SIE in September had a minimum extent of 4.32892 × 106 km^2 in 2020 compared to the much larger SIE of 7.63860 × 106 km^2 in 1982, resulting in a 43% decline over the past four decades."); 13 ("The AICA SIT in March decreased to 1.80 m in 2020 from 3.85 m in 1982, resulting in a 53% decrease at a rate of −0.058 m per year when Arctic sea ice reaches its seasonal maximum extent in the Arctic Ocean. In September, when the Arctic sea ice is at its minimum extent, AICA SIT declined to 0.71 m in 2020 from 1.36 m in 1982, resulting in a 48% decrease at a rate of −0.016 m per year. On an annual average, AICA SIT decreased by 1.22 m, which is 52% of the 2.35 m in 1982, resulting in 1.13 m in 2020. Both PICA and SICA SIT declined to 1.32 m and 0.96 m in 2020 from 2.55 m and 1.86 m in 1982, respectively. All of the Arctic SIT trends in all months are statistically significant, however the SICA SIT trend in September is slightly positive, with a confidence level of 0.496 due to the very small sample size of seasonal ice in September (Table 3)."); 18 ("Over 1982–2020, AICA SIV decreased to 20,679.0 km^3 in 2020 from 51,216.6 km^3 in 1982, resulting in a 60% decrease at a rate of −859.2 km^3 per year in March. In September, AICA SIV declined to 2462.0 km^3 in 2020 from 8931.2 km^3 in 1982, resulting in a 72% decrease at a rate of −170.2 km^3 per year. Based on an annual average, AICA SIV decreased by 17,284.8 km^3, which is 63% of the 27,590.4 km^3 in 1982, resulting in 10,305.5 km^3 SIV in 2020. PICA SIV and SICA SIV declined to 5766.0 km^3 and 4522.8 km^3 in 2020 from 20,313.0 km^3 and 7271.0 km^3 in 1982, respectively. In addition, the ratios of PICA SIV and SICA SIV to AICA SIV were declining in March, when Arctic sea ice reaches its maximum volume over 1982–2020 (Figure 14). It is around 2019 when the SICA SIV proportion started surpassing the PICA SIV proportion in March.").

440 National Snow & Ice Data Center (24 September 2024) *Arctic sea ice extent levels off; 2024 minimum set* ("On September 11, Arctic sea ice likely reached its annual minimum extent of 4.28 million square kilometers (1.65 million square miles). The 2024 minimum is the seventh lowest in the nearly 46-year satellite record. The last 18 years, from 2007 to 2024, are the lowest 18 sea ice extents in the satellite record.").

[441] Meier W. N., Petty A., Hendricks S., Bliss A., Kaleschke L., Divine D., Farrell S., Gerland S., Perovich D., Ricker R., Tian-Kunze X., Webster M. (2024) *Sea Ice*, *in* Arctic Report Card 2024, Moon T. A., Druckenmiller M. L., & Thoman R. L. (eds.), National Oceanic and Atmospheric Administration, 44 ("Age is a proxy for ice thickness because multiyear ice generally grows thicker through successive winter periods. Multiyear ice was largely constrained near the north coast of Greenland and the Canadian Archipelago, with some drifting into the Beaufort and Chukchi Seas (Fig. 2c). Multiyear ice extent has shown interannual oscillations but no clear trend since 2007, reflecting variability in the summer sea ice melt and export out of the Arctic. After a year when substantial multiyear ice is lost, a much larger area of first-year ice generally takes its place. Some of this first-year ice can persist through the following summer, contributing to the replenishment of the multiyear ice extent. However, since 2012, old ice has remained consistently low, less than 5% of the levels in the 1980s. Thus, multiyear ice remains in the Arctic for fewer years than in earlier decades. At the end of summer 2024, multiyear ice extent was similar to 2022 and 2023 values (Fig. 1), 40% of the multiyear extents in the 1980s and 1990s.").

[442] National Snow and Ice Data Center (27 March 2025) *Arctic sea ice hits record low maximum extent for the year* ("Arctic sea ice has likely reached its maximum extent for the year, at 14.33 million square kilometers (5.53 million square miles) on March 22, according to scientists at the National Snow and Ice Data Center (NSIDC) at the University of Colorado Boulder. The 2025 maximum sea ice extent is the lowest in the 47-year satellite record, falling short of the previous record low of 14.41 million square kilometers (5.56 million square miles) set on March 7, 2017.").

[443] Duspayev A., Flanner M. G., & Riihelä A. (2024) *Earth's Sea Ice Radiative Effect From 1980 to 2023*, Geophys. Res. Lett. 51(14): 1–9, 5–6 ("SIRE [sea ice radiative effect] changes over 1980–2023 are calculated in different ways (Table 1). The Theil-Sen linear trend in globally averaged Arctic SIRE, multiplied by 44 years, ranges from 0.17 to 0.22 W m^{-2} across cloud scenarios, with all trends statistically significant at the 95% level, representing a 21%–27% weakening of Arctic SIRE across the timeseries. … Spatial patterns of these changes (Figure 3) show widespread weakening of SIRE throughout the Arctic Ocean, but especially along the eastern periphery of the basin, between the Barents and Beaufort Seas, where sea ice now persists for less of the year or has disappeared completely (e.g., Stroeve & Notz, 2018).").

[444] Wadhams P. (2017) A Farewell to Ice: A Report from the Arctic, Oxford University Press, 107–108 ("Warm air over an ice-free Arctic also causes the snowline to retreat. … This of the same magnitude as the sea ice negative anomaly during the same period, and the change in albedo is roughly the same between snow-covered land and snow-free tundra as it is between sea ice and open water. Nobody has yet published the calculations for tundra as Pistone and her colleagues did for sea ice, but the similarity of the magnitudes means that snowline retreat and sea ice retreat are each adding about the same amount to global warming.").

[445] Westerhold T., *et al.* (2020) *An astronomically dated record of Earth's climate and its predictability over the last 66 million years*, Science 369(6509): 1383–1387, 1387 ("The growth of polar ice sheets at the EOT [Eocene-Oligocene Transition] enhanced the effect of obliquity pacing of high-latitude climate that interacted with eccentricity-modulated precession forcing at lower latitudes from that point in time. This led to increased nonlinear interactions among astronomically paced climate processes and, thus, more complex, stochastic climate dynamics. The development of a large Antarctic ice volume at the inception of the Coolhouse is associated with a fundamental regime change toward less predictable climate variability (lower DET [determinism] values calculated from benthic d^{18}O) (Fig. 3). From 25 to 13.9 Ma DET is elevated again, related to a reduction in ice volume in relatively warmer times of the Coolhouse, culminating in the MCO [Miocene Climatic Optimum] … Thus, not only is polar ice volume critical to defining Earth's fundamental climate state, it also seems to play a crucial role in determining the predictability of its climatological response to astronomical forcing.").

[446] International Cryosphere Climate Initiative (2024) State of the Cryosphere 2024: Lost Ice, Global Damage, 19 ("Glacial melt globally set a record loss in 2023, according to the World Glacier Monitoring Service (WGMS).[1] Reported observations thus far from 2024 indicated record losses in some regions, with Sweden showing the highest melt levels in 80 years of observations.[2] Currently, 2024 is also on a record loss trajectory in Asia .3 Extremely low

snowfall combined with extremely high summer temperatures seem to have contributed to high 2024 loss in these regions.”).

[447] Intergovernmental Panel on Climate Change (2021) *Summary for Policymakers*, ***in*** Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 11 (“Heating of the climate system has caused global mean sea level rise through ice loss on land and thermal expansion from ocean warming. Thermal expansion explained 50% of sea level rise during 1971– 2018, while ice loss from glaciers contributed 22%, ice sheets 20% and changes in land water storage 8%. The rate of ice sheet loss increased by a factor of four between 1992–1999 and 2010–2019. Together, ice sheet and glacier mass loss were the dominant contributors to global mean sea level rise during 2006-2018. (*high confidence*).”).

[448] Zemp M., *et al.* (2025) *Community estimate of global glacier mass changes from 2000 to 2023*, Nature: 1–7, 2 (“The largest contributors to observed global mean sea-level rise (2003–2016: 3.64 ± 0.26 mm yr^{-1})[33] include the steric components (2003–2016: 1.19 ± 0.17 mm yr^{-1}, 33%)[33], owing to changes in ocean temperature and salinity, glaciers (this study, 2002–2021: 0.72 ± 0.04 mm yr^{-1}, 20%), and the Greenland Ice Sheet (2002–2021: 0.62 ± 0.06 mm yr^{-1}, 17%)[17].”).

[449] Slater T., Lawrence I., Otosaka I. Shepherd A., Gourmelen N., Jacob L., Tepes P., Gilbert L., & Nienow P. (2021) *Earth's ice imbalance*, The Cryosphere 15: 233–246, 233 (“The rate of [global] ice loss has risen by 57 % since the 1990s – from 0.8 to 1.2 trillion tonnes per year – owing to increased losses from mountain glaciers, Antarctica, Greenland and from Antarctic ice shelves…. Even though Earth's cryosphere has absorbed only a small fraction of the global energy imbalance [3.2 ± 0.3 %], it has lost a staggering 28 trillion tonnes of ice between 1994 and 2017…. [T]here can be little doubt that the vast majority of Earth's ice loss is a direct consequence of climate warming.”).

[450] European Space Agency (25 January 2021) *Our world is losing ice at record rate* (“A paper, published today in The Cryosphere, describes how a team of researchers led by the University of Leeds in the UK used information from ESA’s ERS, Envisat and CryoSat satellites as well as the Copernicus Sentinel-1 and Sentinel-2 missions to find that the rate at which Earth has lost ice has increased markedly within the past three decades, from 0.8 trillion tonnes per year in the 1990s to 1.3 trillion tonnes per year by 2017. To put this into perspective, one trillion tonnes of ice can be thought of as a cube of ice measuring 10x10x10 km, which would be taller than Mount Everest.”).

[451] Centre national de la recherche scientifique (19 February 2025) *A novel study reveals a significant decline in glaciers on a global scale*, Press Release (“Since 2000, the world's glaciers have lost 5% of their initial volume, and 273 billion tonnes of ice are disappearing every year - the equivalent of 3 Olympic swimming pools per second.”), *discussing* Zemp M., *et al.* (2025) *Community estimate of global glacier mass changes from 2000 to 2023*, Nature: 1–7.

[452] Mallett R. D. C., Stroeve J. C., Tsamados M., Landy J. C., Willatt R., Nandan V., & Liston G. E. (2021) *Faster decline and higher variability in the sea ice thickness of the marginal Arctic seas when accounting for dynamic snow cover*, The Cryosphere 15(5): 2429–2450, 2429, 2441 (“When the sea ice thickness in the period 2002–2018 is calculated using new snow data with more realistic variability and trends, we find mean sea ice thickness in four of the seven marginal seas to be declining between 60 %–100 % faster than when calculated with the conventional climatology. … We first assess regions where SIT [sea ice thickness] was already in statistically significant decline when calculated with mW99. This is the case for all months in the Laptev and Kara seas and 4 of 7 months in the Chukchi and Barents sea. The rate of decline in these regions grew significantly when calculated with SnowModel-LG data (Fig. 10; green panels). Relative to the decline rate calculated with mW99, this represents average increases of 62% in the Laptev sea, 81% in the Kara Sea and 102% in the Barents Sea. The largest increase in an already statistically significant decline was in the Chukchi Sea in April, where the decline rate increased by a factor of 2.1. When analysed as an aggregated area and with mW99, the total marginal seas area exhibits a statistically significant negative trend in November, December, January and April. The East Siberian Sea is the only region to have a month of decline when calculated with mW99 but not with SnowModel-LG.”).

[453] Wang Q., Wekerle C., Wang X., Danilov S., Koldunov N., Sein D., Sidorenko D., von Appen W.-J., & Jung T. (2020) *Intensification of the Atlantic Water Supply to the Arctic Ocean Through Fram Strait Induced by Arctic Sea Ice Decline*, GEOPHYS. RES. LETT. 47(3): 1–10, 1 ("The reduction in sea ice export through Fram Strait induced by Arctic sea ice decline increases the salinity in the Greenland Sea, which lowers the sea surface height and strengthens the cyclonic gyre circulation in the Nordic Seas. The Atlantic Water volume transport to the Nordic Seas and Arctic Ocean is consequently strengthened. This enhances the warming trend of the Arctic Atlantic Water layer, potentially contributing to the Arctic "Atlantification." … In these processes, the Nordic Seas play the role of a switchyard, while the reduction of sea ice export flux caused by increased air-sea heat flux over the Arctic Ocean is the switchgear. Increasing ocean heat can reduce sea ice thickness, and currently this occurs mainly in certain regions including the western Eurasian Basin near the Fram Strait and the northern Kara Sea (Carmack et al., 2015; Dmitrenko et al., 2014; Ivanov et al., 2012; Onarheim et al., 2014; Polyakov et al., 2010).").

[454] MacKinnon J. A., *et al.* (2021) *A warm jet in a cold ocean*, NAT. COMMUN. 12(2418): 1–12, 1 ("Unprecedented quantities of heat are entering the Pacific sector of the Arctic Ocean through Bering Strait, particularly during summer months. Though some heat is lost to the atmosphere during autumn cooling, a significant fraction of the incoming warm, salty water subducts (dives beneath) below a cooler fresher layer of near-surface water, subsequently extending hundreds of kilometers into the Beaufort Gyre. Upward turbulent mixing of these sub-surface pockets of heat is likely accelerating sea ice melt in the region. This Pacific-origin water brings both heat and unique biogeochemical properties, contributing to a changing Arctic ecosystem.").

[455] Barton B. I., Lenn Y.-D., & Lique C. (2018) *Observed Atlantification of the Barents Sea Causes the Polar Front to Limit the Expansion of Winter Sea Ice*, J. PHYS. OCEANOGR. 48(8): 1849–1866, 1866 ("Our results provide new evidence that, in addition to the natural multidecadal variability, the Barents Sea is currently undergoing Atlantification, with the corresponding temperature and salinity increases catalyzed by the observed PF [polar front] constraint on the sea ice edge. The loss of winter sea ice south of the front represents a loss of freshwater input to BSW [Barents Sea Water], a water mass that makes up 50%–80% of AIW [Arctic Intermediate Water]. As the stationary PF, rather than the mobile sea ice edge, has become the limiting factor controlling the northern boundary of the surface area available for AW [Atlantic Water] cooling in winter, the buffering effect to BSW temperature from the variations of sea ice conditions has decreased. Observations show a change in BSW properties over the same time period resulting in denser BSW, which could in turn result in a deeper settling depth of BSW once exported to the Arctic basin through St. Anna Trough (Dmitrenko et al. 2015), with potential far-reaching impacts for the dense water outflow through Fram Strait (Lique et al. 2010; Moat et al. 2014) or the density of the Denmark Strait overflow (Karcher et al. 2011), both of which are important for the deeper branch of the AMOC.").

[456] Shu Q., Wang Q., Song Z., & Qiao F. (2021) *The poleward enhanced Arctic Ocean cooling machine in a warming climate*, NAT. COMMUN. 12(2966): 1–9, 6 ("Most of the CMIP6 models consistently show a poleward advance of the Arctic Ocean cooling machine and Arctic Atlantification (Supplementary Figs. 7–14). The significant model spreads in the simulated linear trends of sea ice concentration, sea surface heat flux, MLD [mixed layer depth], and sea surface stress (Supplementary Fig. 15) imply possible uncertainties in the predicted timing and strength of the changes in the cooling machine and Arctic Atlantification represented by the MMM [multi-model mean]. In particular, the underestimated trends in sea ice decline, ocean surface heat flux, and MLD in the CMIP6 MMM compared to observations and reanalysis as shown in Fig. 2 imply that the future development of the poleward expansion of the cooling machine and the strengthening of Arctic Atlantification are very possibly underestimated in the CMIP6 models on average.").

[457] Isaksen K., *et al.* (2022) *Exceptional warming over the Barents sea*, SCI. REP. 12(9371): 1–18, 1 ("Both the SAT [surface air temperature] analysis from instrumental records[8] and widely used reanalyses products, including ERA5, point to a maximum warming area in the Barents region (Fig. 1). This Arctic warming hotspot[10] is not constrained to the warming atmosphere; the Northern Barents Sea (NBS) region also hosts the most pronounced loss of Arctic winter sea ice[11] and has since the early 2000s experienced a sharp increase in both temperature and salinity in the entire water column. The decline in the Barents sea ice cover, increased ocean temperature and salinity are closely related to the higher temperatures in the Atlantic Water and increased ocean heat transport entering the region from the west[12,13,14]. In addition, the increase in salinity is larger towards the upper layers, leading to a weakened ocean stratification and

hereby an increased upward heat flux[10]. These oceanographic processes strongly contribute to the amplified warming in the region and enable larger heat flux interaction between the ocean and the air. If the rise in ocean temperature and salinity continues, the originally cold and stratified Arctic shelf region may be transformed into an Atlantic-dominated climate regime with a warmer and more well-mixed water column strongly preventing sea ice formation[10].").

[458] McIntyre M. E. (2023) *Climate tipping points: A personal view*, PHYSICS TODAY 76(3), 44–49, 47 ("When viewed in finer detail, the warming events often seem to have involved more than one sharp stepwise jump within a few decades, with each jump taking only a few years. The mechanisms in play are exceedingly complex. In particular, the warming events are related to global-scale oceanic and atmospheric circulations and sea-ice cover, especially in the Nordic Seas, between Scandinavia and Greenland.[5–8] With one exception, however, the mechanisms considered have time scales too long to produce the sharp jumps. The exceptional mechanism—the only mechanism suggested so far that is fast enough—involves the Nordic sea ice and the fine structure of upper-ocean layering underneath the ice.[6,7] The exceptional mechanism depends on the northward inflow of warm, salty subsurface Atlantic water under the sea ice. During cold intervals, the uppermost layers of the Nordic Sea were stably stratified with a strong halocline—a boundary that separates the warm, salty subsurface Atlantic inflow from colder, fresher, more buoyant upper layers capped by sea ice…. But if the subsurface inflow warms enough, the water can become sufficiently buoyant to break through the halocline and up to the surface, where it quickly melts the sea ice. When such sudden sea-ice melting happens over a substantial area, or in steps over a succession of substantial areas, the atmosphere can respond quickly with major changes in its weather patterns on a hemispheric scale. Today some areas in the Arctic Ocean may be approaching a similar state, albeit still short of buoyant breakthrough.[10] Recent underwater observations made in 2003–18 show a weakening halocline being eroded by turbulent mixing, which allows more subsurface heat to reach the surface, at rates that increased from 3–4 W m^{-2} in 2007–08 to about 10 W m^{-2} in 2016–18. As buoyant breakthrough conditions are approached, the current rate of sea-ice melting—already accelerating through the well-known ice-albedo feedback—may likely accelerate further and more drastically. As with the Dansgaard–Oeschger warmings, there could be several such episodes of increased acceleration as different areas of Arctic sea ice are melted in a stepwise fashion. Exactly what will happen is extremely hard to predict since, in climate models, the fine structure of the upper ocean with its halocline and sea ice, the associated buoyancy-related and turbulent-mixing processes, and the subsurface ocean currents and eddies are not accurately represented in enough detail. But an educated guess would be to anticipate a drastic acceleration of Arctic sea-ice loss quite soon, perhaps over the next decade or two, with knock-on effects that could include accelerated melting of the Greenland ice sheet.").

[459] Thomson J. & Rogers W. E. (2014) *Swell and sea in the emerging Arctic Ocean*, GEOPHYS. RES. LETT. 41(9): 3136–3140, 3136 ("Ocean surface waves (sea and swell) are generated by winds blowing over a distance (fetch) for a duration of time. In the Arctic Ocean, fetch varies seasonally from essentially zero in winter to hundreds of kilometers in recent summers. Using in situ observations of waves in the central Beaufort Sea, combined with a numerical wave model and satellite sea ice observations, we show that wave energy scales with fetch throughout the seasonal ice cycle. Furthermore, we show that the increased open water of 2012 allowed waves to develop beyond pure wind seas and evolve into swells. The swells remain tied to the available fetch, however, because fetch is a proxy for the basin size in which the wave evolution occurs. Thus, both sea and swell depend on the open water fetch in the Arctic, because the swell is regionally driven. This suggests that further reductions in seasonal ice cover in the future will result in larger waves, which in turn provide a mechanism to break up sea ice and accelerate ice retreat.").

[460] Finocchio P. M. & Doyle J. D. (2022) *Summer Cyclones and Their Association With Short-Term Sea Ice Variability in the Pacific Sector of the Arctic*, FRONT. EARTH SCI. 9(738497): 1–17, 15 ("The advective tendency of SIC [sea ice concentration] due to the 10-m wind is one of the most consistent predictors of both local and regional ice loss for the large sample of cyclones in the ECB [East Siberian, Chukchi, and Beaufort Seas] region. We find the strongest relationship between advection and sea ice loss for low concentration sea ice in August. This supports previous studies arguing that the reduced mechanical strength of lower concentration sea ice makes it more susceptible to wind-induced drift and deformation (Hakkinen et al., 2008; Rampal et al., 2009; Spreen et al., 2011). "). *See also* Finocchio P. M., Doyle J. D., & Stern D. P. (2022) *Accelerated Sea-Ice Loss from Late-Summer Cyclones in the New Arctic*, J. CLIM.: 1–39, 1 ("We compare the 1-7 day changes in sea-ice area and thickness following days in each month with and without cyclones from two decades: 1991-2000 and 2009-2018. Only in August do cyclones locally accelerate seasonal sea-ice loss on average, and the ability of August cyclones to accelerate ice loss has become more pronounced

in the recent decade. The recent increase in ice loss following August cyclones is most evident in the Amerasian Arctic (140°E-120°W), where reanalyses indicate that the average upper-ocean temperature has increased by 0.2-0.8°C and the average ice thickness has decreased by almost 1 m between the two decades. Such changes promote cyclone-induced ocean mixing and sea-ice divergence that locally increase the likelihood for rapid ice loss near cyclones. In contrast, June cyclones in both decades locally slow down seasonal sea-ice loss. Moreover, the 7-day sea-ice loss in June has increased from the early to the recent decade by 67% more in the absence of cyclones than in the presence of cyclones. The largest increases in June ice loss occur in the Eurasian Arctic (0-140°E), where substantial reductions in average surface albedo in the recent decade have allowed more of the abundant insolation in the absence of cyclones to be absorbed at the sea surface."). Research is also underway that analyzes 2022 trends for accelerated ice loss in the Arctic due to late summer cyclones: *see* Hand E. (23 August 2022) *Arctic stormchasers brave giant cyclones to understand how they chew up sea ice*, SCIENCE.

461 Valkonen E., Cassano J., & Cassano E. (2021) *Arctic Cyclones and their Interactions With the Declining Sea Ice: A Recent Climatology*, J. GEOPHYS. RES. ATMOS. 126(12): 1–35, 20 ("One of the most intriguing results in our analysis of track counts was the strong positive trend in cyclone numbers from ∼2,000 onward in the cold season (Figure 3) and its connection to the decreasing SIC. Increased number of cyclones has also been observed in many other studies (Rudeva & Simmonds, 2015; Sepp & Jaagus, 2011; Zahn et al., 2018), but the positive trends found in Sepp and Jaagus (2011) and Zahn et al. (2018) were not spatially coherent, and some studies have also found negative or nonsignificant cyclone trends (e.g., Simmonds & Keay, 2009). The connection between cyclones and the changing sea ice surface has also remained unclear. The results presented here show a more coherent cold season increase in the cyclone counts than previous studies have. We also showed that the increased cyclone counts in the cold season were indeed connected to the declining sea ice in both the warm and cold seasons (Figures 11and A15). Less sea ice in the cold season or the following warm season was related to increased cyclone counts in the cold season. This was apparent in both the correlation tables and trend matrix figures (Tables 1 and A1, and Figures 3, 11, and A15). The negative correlation between the warm season SIC and cold season cyclones could be supported by the findings of Koyama et al. (2017), which connected low summer sea ice years with more favored conditions for cyclogenesis the following fall/winter. However, they did not find an increase in the number of cyclones associated with the declining sea ice, which our results clearly showed."). *See also* Day J. J. & Hodges K. I. (2018) *Growing Land-Sea Temperature Contrast and the Intensification of Arctic Cyclones*, GEOPHYS. RES. LETT. 45: 3673–3681, 3680 ("In summary, we observed: 1. that 2m land temperatures near the Arctic coastline are warming at approximately twice the rate of sea surface temperatures in adjacent regions; 2. that significantly increased Arctic cyclone frequency and intensity, particularly in the Eastern part of the Arctic Ocean, are characteristic of years with high Arctic coastal temperature gradients, compared to low years; and 3. that the sign of this response is consistent with climate model projections, but the magnitude of change in cyclone numbers is higher, suggesting that CMIP models underestimate the sensitivity of the summer storm track to increasing land-sea contrast in the Arctic. Further, because climate change is increasing land-sea contrasts in the Arctic, it seems highly likely that the circulation patterns typical of years with strong AFZ will become more common as the climate warms. Indeed, strengthening of the mean temperature gradients in the AFZ is a robust feature of future climate projections as is an increase in the strength of the Arctic Front Jet (Mann et al., 2017; Nishii et al., 2014). This study shows that this linkage between surface temperature gradients and atmospheric circulation is important for Arctic cyclones, adding weight to previous studies.").

464 International Cryosphere Climate Initiative (2024) STATE OF THE CRYOSPHERE 2024: LOST ICE, GLOBAL DAMAGE, 42 ("The occurrence of the first sea ice-free Arctic summer is therefore difficult to predict, but scientists now believe it is inevitable, and likely to occur at least once before 2050 even under a "very low" emissions scenario.[10,12,15,41] … In contrast, continuing on the current emissions trajectory may lead to the Arctic becoming ice free in the summer as soon as the 2030s.[25] Even moderate emissions will lead to ice-free conditions most summers once global mean temperature rise reaches about 1.7°C. The length of this ice-free state would increase in lock-step with emissions and temperature,[26,40–42] eventually stretching from July–October at 2°C.[1,26,43] The effects of amplifying feedbacks will be widespread, ranging from accelerated loss of ice and associated sea-level rise from Greenland; to losses of ice-dependent species; to greater permafrost thaw, leading to even larger carbon emissions and infrastructure damage.[12,40]"). Note that there is a difference between the *first* occurrence of a sea ice-free Arctic and a *consistently* sea-ice free Arctic. Additionally, different studies use different thresholds to define a sea ice-free month; for a review,

see Jahn A., Holland M. M., & Kay J. E. (2024) *Projections of an ice-free Arctic Ocean*, NAT. REV. EARTH ENVIRON. 5(3): 164–176, 164 ("In the September monthly mean, the earliest ice-free conditions (the first single occurrence of an ice-free Arctic) could occur in 2020–2030s under all emission trajectories and are likely to occur by 2050. However, daily September ice-free conditions are expected approximately 4 years earlier on average, with the possibility of preceding monthly metrics by 10 years. Consistently ice-free September conditions (frequent occurrences of an ice-free Arctic) are anticipated by mid-century (by 2035–2067), with emission trajectories determining how often and for how long the Arctic could be ice free.").

[465] Armstrong McKay D. I. & Loriani S. (eds.) (2023) *Section 1: Earth systems tipping points*, in GLOBAL TIPPING POINTS REPORT 2023, Lenton T. M., et al. (eds.), 101 ("In the case of sustained Arctic summer sea ice loss, which may occur during the second half of this century (Niederdrenk et al., 2018) or sooner (Kim et al., 2023), additional warming levels are in the order of 0.3-0.5°C regionally over Greenland and the permafrost (Wunderling et al., 2020). Regional warming levels may be higher if Arctic winter sea ice also disappears under high-emission scenarios. Further, it has been found that regional Arctic sea ice loss has a limited effect for Greenland warming patterns and is mainly relevant for coastal parts of Greenland (Pedersen and Christensen, 2019). At the same time, Arctic sea ice loss leads to increased coastal permafrost erosion (Hošeková et a., 2021; Casas-Prat and Wang, 2020; Grigoriev et al., 2019; Nielsen et al., 2020 and 2022). Abrupt changes in summer-autumn seaice retreat from the permafrost coast leads to an increase in waves, resulting in sudden increases in erosion rates (– about 50-160 per cent in the last 50 years (a two-to fourfold increase in hotspots in the Laptev and Beaufort Seas) (Irrgang et al., 2022). Thus, coastal permafrost collapse leads to a potential cascading risk of carbon releases locally to the Arctic ocean and the atmosphere of 0.0023–0.0042 GtC per year per degree celsius by the end of the century (Nielsen et al., 2022).").

[466] Armstrong McKay D. I. & Loriani S. (eds.) (2023) *Section 1: Earth systems tipping points*, in GLOBAL TIPPING POINTS REPORT 2023, Lenton T. M., et al. (eds.), 20 ("However, a large variety of studies based on both conceptual models and coupled Earth system models have provided convincing evidence that the summer ice-albedo feedback is compensated by damping feedbacks in winter that minimise the long-term memory of the Arctic summer sea ice cover (Figure 1.2.8). This dominance of negative/damping feedbacks gives rise to a linear retreat of the Arctic summer sea ice cover with ongoing global warming (e.g., Gregory et al., 2002; Winton, 2006; Winton, 2008; Notz, 2009; Tietsche et al., 2011; Mahlstein and Knutti, 2012: Wagner and Eisenman, 2015).").

[467] Sadatzki H., Maffezzoli N., Dokken T. M., Simon M. H., Berben S. M. P., Fahl K., Kjær H. A., Spolaor A., Stein R., Vallelonga P., Vinther B. M., & Jansen E. (2020) *Rapid reductions and millennial-scale variability in Nordic Seas sea ice cover during abrupt glacial climate changes*, PROC. NAT'L. ACAD. SCI. 117(47): 29478–29486, 29485 ("In conclusion, our study provides unprecedentedly detailed, spatially coherent, and temporally constrained and consistent empirical evidence that resolves rapid large-scale sea ice decline in the Nordic Seas occurring concomitantly with the glacial D-O [Dansgaard-Oeschger events], after an initial seasonal sea ice reduction in the southern Norwegian Sea. Our results thus strongly support that rapid sea ice decline and associated positive feedbacks shaped the transition from surface stratification to deep ocean convection in the Nordic Seas and acted as critical tipping element that amplified and possibly initiated the abrupt D-O climate change (10, 61). Our findings also raise questions as to whether the currently observed Arctic sea ice decline will lead to a similar destabilization of surface stratification and to what extent this will further amplify climate warming in the Arctic."); 29483 ("The rapid large-scale sea ice decline in the Nordic Seas matches a rapid ∼2–3 °C overshoot in near-surface temperature and an ∼1‰ increase in benthic $\delta^{18}O$, recorded in MD99-2284 (Fig. 5). The increase in benthic $\delta^{18}O$ probably reflects deep-water cooling by ∼2–3 °C, as supported by independent benthic foraminiferal Mg/Ca-based evidence (21, 22) (Fig. 3E). The near-surface temperature overshoot reflects maximum inflow of warm and saline Atlantic surface waters into the Norwegian Sea, while the deep-water cooling suggests deep-ocean convection (21, 22, 24). The concurrence and rapidity of surface and deep-water temperature changes at site MD99-2284 and the major sea ice decline, recorded at site MD95-2010 and in the RECAP ice core, are supported by the tight alignment of rather gradual ARM increases at the GS-GI transitions in both sediment cores. Our results thus testify that the rapid sea ice decline shaped threshold response of both deep convection in the Nordic Seas and D-O climate transitions in Greenland (9, 10).").

[468] Guarino M.-V., *et al.* (2020) *Sea-ice-free Arctic during the Last Interglacial supports fast future loss*, NAT. CLIM. CHANGE 10: 928–932, 929, 931, 932 ("Our study has demonstrated that the high-ECS [equilibrium climate sensitivity]

HadGEM3 model yields a much-improved representation of Arctic summers during the warmer LIG [Last Interglacial] climate compared with previous old-generation model simulations. We analysed simulated surface air temperatures and proxy reconstructions of LIG summer temperatures and showed a 95% agreement between the model and observations. Arctic surface temperatures and sea ice are strongly related. By simulating an ice-free summer Arctic, our LIG CMIP6 simulation provides (direct) modelling and (indirect) observational support that the summer Arctic could have been ice free during the LIG. This offers a unique solution to the long-standing puzzle of what occurred to drive the temperatures to rise during LIG Arctic summers. The ability of the HadGEM3 model to realistically simulate the very warm LIG Arctic climate provides independent support for predictions of ice-free conditions by summer 2035. This should be of huge concern to Arctic communities and climate scientists. … The LIG sea-ice decrease commences in June (when the LIG sea-ice extent is outside of the PI range of variability, Fig. 1a) and culminates in a complete loss of ice by the end of the melt season in August and September (Fig. 1a,f). … The predicted year of disappearance of September sea ice under high-emissions scenarios is 2086 for HadCM3 (CMIP3/5), 2048 for HadGEM2-ES (CMIP5) and 2035 for HadGEM3 (CMIP6) (Fig. 4).”). *See also* Jahn A., Holland M. M., & Kay J. E. (2024) *Projections of an ice-free Arctic Ocean*, NAT. REV. EARTH ENVIRON. 5(3): 164–176, 167 (“There is also evidence for ice-free conditions in the more recent geological past. For example, the last ice-free conditions in the Arctic likely occurred during the Eemian — the warmest period of the warmest quaternary interglacials — including marine isotope stage 5e (MIS 5e) (between 130,000 and 115,000 years ago) and potentially MIS 5a (around 80,000 years ago). At these times, proxy records indicate open water north of Greenland[131–135] and a northward shift of the tree line by hundreds of kilometres in Alaska and Russia[126,136]; note that paleo evidence for these changes is stronger for MIS 5e than MIS 5a.”)

[469] Crawford A., Stroeve J., Smith A., & Jahn A. (2021) *Arctic open-water periods are projected to lengthen dramatically by 2100*, COMMUN. EARTH ENVIRON. 2(109): 1–10, 4 (“The rate of increase in open-water period is comparable for all three emissions scenarios until the 2040s (Fig. 2), when the rate of change declines in SSP126 (blue), persists in SSP245 (orange), and accelerates in SSP585 (red). The most southerly regions (Sea of Okhotsk, Bering Sea, Gulf of St. Lawrence, and Labrador Sea) become ice-free year-round by the end of the century in SSP585, and some models also show the Greenland and Barents seas reach 365 days of open water for all grid cells by 2100.”). *See also* Årthun M., Onarheim I. H., Dörr J., & Eldevik T. (2021) *The seasonal and regional transition to an ice-free Arctic*, GEOPHYS. RES. LETT. 48: 1–10, 1 (“The Arctic sea ice cover is currently retreating and will continue its retreat in a warming world. However, the loss of sea ice is neither regionally nor seasonally uniform. Here we present the first regional and seasonal assessment of future Arctic sea ice loss in CMIP6 models under low (SSP126) and high (SSP585) emission scenarios, thus spanning the range of future change. We find that Arctic sea ice loss – at present predominantly limited to the summer season – will under SSP585 take place in all regions and all months. The summer sea ice is lost in all the shelf seas regardless of emission scenario, whereas ice-free conditions in winter before the end of this century only occur in the Barents Sea. The seasonal transition to ice-free conditions is found to spread through the Atlantic and Pacific regions, with change starting in the Barents Sea and Chukchi Sea, respectively.”); *and* Tor Eldevik (@TorEldevik), Twitter, 7 December 2020, 6:43AM (Co-author on the study sharing graphics and information about the ice-free conditions in the shelf seas).

[470] Jahn A., Holland M. M., & Kay J. E. (2024) *Projections of an ice-free Arctic Ocean*, NAT. REV. EARTH ENVIRON. 5(3): 164–176, 170 (“In terms of temperature, the earliest ice-free conditions could occur for warming >1.3 °C, are likely to occur for warming of 1.8 °C (Table 1; Fig. 3d), and exhibit a range of 0.9–3.2 °C (ref. 10) that can be refined to 1.3–2.9 °C (refs. 10,74,78,96).”). *See also* Poltronieri A., Bochow N., Aksamit N. O., Boers N., Jakobsen P. K., & Rypdal M. (2024) *Arctic summer sea ice loss will accelerate in coming decades*, ENVIRON. RES. LETT. 19(7): 1–7, 1 (“Our analysis of observations and CMIP6 model data suggests a complete loss of the September ASI (area below 10^6 km^2) for global warming between 1.5 ◦C and 2.2 ◦C above pre-industrial GMST levels.”). Individual days of ice-free conditions are likely to occur much sooner; *see* Heuzé C. & Jahn A. (2024) *The first ice-free day in the Arctic Ocean could occur before 2030*, NAT. COMMUN. 15(1): 1–10, 7 (“We showed that the earliest ice-free day in the Arctic Ocean could occur within 3 years from 2023 sea ice area (SIA) minimum equivalent conditions, i.e. that there is a non-zero probability of an ice-free day before 2030. The highest probability of the earliest ice-free day occurring lies within 7–20 years, based on the earliest ensemble member from all SSPs from the 11 CMIP6 models analyzed (Fig. 1).”).

[471] Poltronieri A., Bochow N., Aksamit N. O., Boers N., Jakobsen P. K., & Rypdal M. (2024) *Arctic summer sea ice loss will accelerate in coming decades*, ENVIRON. RES. LETT. 19(7): 1–7, 5 ("We confirm the robustness of our results by repeating the analysis on an independent observational sea ice data set, the Sea Ice Index, Version 3 [30]. This additional observation-based projection confirms our conclusions and exhibits an accelerated non-linear decline of the ASI area with ice-free conditions predicted for global warming between 1.5 ◦C and 2.2 ◦C above pre-industrial GMST levels (figure S4).").

[472] Jahn A., Holland M. M., & Kay J. E. (2024) *Projections of an ice-free Arctic Ocean*, NAT. REV. EARTH ENVIRON. 5(3): 164–176, 171, 173 ("Consistently ice-free conditions are expected by mid-century, potentially under all warming scenarios[78]."; "Ice loss is also expected beyond the months of September, particularly the shoulder months of August and October, but with marked temperature sensitivity. Thus, greenhouse gas mitigation strongly affects ice-free conditions, determining how often, for how long and where the Arctic will lose its sea ice cover. In particular, under the low-warming scenarios (SSP1-2.6), with warming remaining well below 2 °C, ice-free conditions could remain an exception rather than the new normal[76].").

[473] Bonan D. B., Schneider T., Eisenman I., & Wills R. C. J. (2021) *Constraining the Date of a Seasonally Ice-Free Arctic Using a Simple Model*, GEOPHYS. RES. LETT. 48(18): 1–12, 1 ("Under a high-emissions scenario, an ice-free Arctic will likely (>66% probability) occur between 2036 and 2056 in September and between 2050 and 2068 from July to October. Under a medium-emissions scenario, the "likely" date occurs between 2040 and 2062 in September and much later in the 21st century from July to October."). However, findings of ice-free September Arctic sea ice may be too early by a decade if models are not properly accounting for larger changes in atmospheric circulation, *according to* Topál D. & Ding Q. (2023) *Atmospheric circulation-constrained model sensitivity recalibrates Arctic climate projections*, NAT. CLIM. CHANG. 1–9, 5 ("To showcase our point, we use the abovementioned method to constrain the timing of the first sea-ice-free September in the SMILEs and CMIP6 models. The cumulative probability density functions (CDFs) corresponding to the time of emergence of the first seasonally sea-ice-free Arctic[52,5]3 (below 1 million km^2 in September) in the raw and the calibrated SIE time series in the model ensembles show prospects of a 9–11-year delay of the 'likely' (in IPCC[54] terms) probability ($P > 0.66$) of a September ice-free Arctic, such that an ice-free summer before 2050 is 'as likely as not' (in IPCC terms $0.33 < P < 0.66$) (Fig. 5c; Methods). This result is in contrast to estimates from previous studies that project ice-free September as early as mid-century[33]. Our results are also at odds with a recent study, where the authors used Arctic temperatures as an emergent constraint on ice-free projections in CMIP6 (ref. 40)."). In addition, a *consistently* sea ice-free Arctic in September and other months will occur later, than the *first* time the Arctic is sea ice-free for a given month or season; *see* Jahn A., Holland M. M., & Kay J. E. (2024) *Projections of an ice-free Arctic Ocean*, NAT. REV. EARTH ENVIRON. 5(3): 164–176, 171 ("For example, there is a possibility of occasional ice-free conditions in August and October with <2 °C warming (or SSP1-1.9) (refs. 76,85), extending into July with ≥2.5 °C warming (or SSP1-2.6) and into November with ≥3.5 °C warming (or SSP2-4.5) (Fig. 4). In some select CMIP6 models under SSP5-8.5, first ice-free conditions also occur in December, January, May and June during the second half of the twenty-first century (Fig. 4d) when warming exceeds 3.5 °C (ref. 114). … For the selected CMIP6 models forced with SSP2-4.5, the ice-free season is expected to span 3 months per year by 2100 (as determined by continuous likely (>66%) ice-free conditions): ice-free conditions emerge in August by approximately 2055 and in October by approximately 2080 (Fig. 4c). In contrast, the likely ice-free season is expected to span 6 months for SSP5-8.5: beyond September, continuous ice-free conditions emerge in August by approximately 2050, in October by approximately 2055, in November by approximately 2070, in July by approximately 2075 and in December by approximately 2090 (ice-free conditions in July to October become very likely or virtually certain by 2100) (Fig. 4d). Consistently ice-free conditions are not expected beyond September for SSP1-1.9 (Fig. 4a) or SSP1-2.6 (Fig. 4b).").

[474] Pistone K., Eisenman I., & Ramanathan V. (2019) *Radiative Heating of an Ice-Free Arctic Ocean*, GEOPHYS. RES. LETT. 46(13): 7474–7480, 7477 ("This heating of 0.71 W/m^2 is approximately equivalent to the direct radiative effect of emitting one trillion tons of CO_2 into the atmosphere (see calculation in Appendix A). As of 2016, an estimated 2.4 trillion tons of CO_2 have been emitted since the preindustrial period due to both fossil fuel combustion (1.54 trillion tons) and land use changes (0.82 trillion tons), with an additional 40 billion tons of CO_2 per year emitted from these sources during 2007–2016 (Le Quéré et al., 2018). Thus, the additional warming due to the complete loss of Arctic

sea ice would be equivalent to 25 years of global CO_2 emissions at the current rate."). *See also* Institute for Governance & Sustainable Development (2019) *Plain Language Summary of Pistone K., et al*.

[475] Pistone K., Eisenman I., & Ramanathan V. (2019) *Radiative Heating of an Ice-Free Arctic Ocean*, GEOPHYS. RES. LETT. 46(13): 7474–7480, 7479 ("The estimate of one trillion tons of CO_2 emissions is computed using the following approximate formula: $f = (5.35\ W/m^2)\ \ln[x/R]$ (Myhre et al., 1998). Here f is the radiative forcing relative to an arbitrary reference value R, x is the atmospheric CO_2 concentration, and ln indicates the natural logarithm. Note that this formula is an expression of the relationship that a doubling of atmospheric CO_2 causes a radiative forcing of 3.71 W/m^2. Considering a radiative forcing of 0.71 W/m^2, this translates to an increase in the atmospheric CO_2 concentration from 400 to 456.7 ppm. Since 1 ppm of atmospheric CO_2 is equivalent to 7.77 Gt (Le Quéré et al., 2018), this increase of 56.7 ppm weighs 441 Gt. The mean airborne fraction of CO_2 (i.e., fraction of CO_2 emissions that remain in the atmosphere) is estimated to be 0.44 ± 0.06 (section 6.3.2.4 of Ciais et al., 2013). This implies that the emissions needed to increase atmospheric CO_2 enough to cause 0.71 W/m^2 of radiative forcing is 1.0 trillion tons (i.e., 441 Gt/0.44).").

[476] Pistone K., Eisenman I., & Ramanathan V. (2019) *Radiative Heating of an Ice-Free Arctic Ocean*, GEOPHYS. RES. LETT. 46(13): 7474–7480, 7476 ("Hence, we focus on the baseline estimate scenario in which cloud conditions remain unchanged from the present. We find that the complete disappearance of Arctic sea ice throughout the sunlit part of the year in this scenario would cause the average planetary albedo of the Arctic Ocean (poleward of 60 ºN) to decrease by 11.5% in absolute terms. This would add an additional 21 W/m^2 of annual-mean solar heating over the Arctic Ocean relative to the 1979 baseline state. Averaged over the globe, this implies a global radiative heating of 0.71 W/m^2 (Figure 2)."). *See also* Wunderling N., Willeit M., Donges J. F., & Winklemann R. (2020) *Global warming due to loss of large ice masses and Arctic summer sea ice*, NAT. COMMUN. 11(5177): 1–8, 6 ("On shorter time scales, the decay of the Arctic summer sea ice would exert an additional warming of 0.19 °C (0.16–0.21 °C) at a uniform background warming of 1.5 °C (=400 ppm) above pre-industrial. On longer time scales, which can typically not be considered in CMIP projections, the loss of Greenland and West Antarctica, mountain glaciers and the Arctic summer sea ice together can cause additional GMT warming of 0.43°C (0.39–0.46 °C). This effect is robust for a whole range of CO_2 emission scenarios up to 700 pm and corresponds to 29% extra warming relative to a 1.5 °C scenario."). If the Greenland Ice Sheet, West Antarctic Ice Sheet, and mountain glaciers were also completely ice-free, the planet could see an additional 0.43 ºC of warming, with 55% of that coming from the loss of albedo.

[477] Forster P., Storelvmo T., Armour K., Collins W., Dufresne J.-L., Frame D., Lunt D. J., Mauritsen T., Palmer M. D., Watanabe M., Wild M., & Zhang H. (2021) *Chapter 7: The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 7-49 (Table 7.8 gives Effective Radiative Forcings (ERF) for CO_2 of 2.16 (1.90 to 2.41)). *See also* National Oceanic and Atmospheric Administration Global Monitoring Laboratory, *The NOAA Annual Greenhouse Gas Index (AGGI)* (*last visited* 14 February 2023) (Table 2 shows that the radiative forcing from CO_2 was 2.079 W/m^2 in 2019, 2.111 W/m^2 in 2020, and 2.140 W/m^2 in 2021.)

[478] Pistone K., Eisenman I., & Ramanathan V. (2019) *Radiative Heating of an Ice-Free Arctic Ocean*, GEOPHYS. RES. LETT. 46(13): 7474–7480, 7477 ("We examine two perhaps unrealistically extreme future Arctic cloud scenarios: at one extreme, an ice-free Arctic Ocean that is completely cloud free and at the other extreme, an ice-free Arctic Ocean that is completely overcast. For simplicity, in the latter scenario we use distributions of cloud optical thickness based on present-day observations (see Appendix A). Both of these extreme scenarios are shown in Figure 2. The cloud-free, ice-free Arctic scenario results in a global radiative heating of 2.2 W/m^2 compared with the 1979 baseline state, which is 3 times more than the 0.71 W/m^2 baseline estimate derived above for unchanged clouds. The completely overcast ice-free Arctic scenario results in a global radiative heating of 0.37 W/m^2, which is approximately half as large as the 0.71 W/m^2 baseline estimate (Figure 2b). This suggests that even in the presence of an extreme negative cloud feedback, the global heating due to the complete disappearance of the Arctic sea ice would still be nearly double the already-observed heating due to the current level of ice loss.").

[479] United States Environmental Protection Agency (2015) U.S. NATIONAL BLACK CARBON AND METHANE EMISSIONS: A REPORT TO THE ARCTIC COUNCIL, 2, 9 (Figure 1 shows BC [black carbon] emissions north of the 40th

parallel in 2011 amounting to 0.51 million metric tons, with 39% from open biomass burning, and 51% of that number [19.89% or ~0.10 MMT] due to wildfires; "In 2011, 51 percent of black carbon emissions from open biomass burning were from wildfires, 43 percent from prescribed burning, with the remainder from agricultural field burning."). *See also* Kim J.-S., Kug J.-S., Jeong S.-J., Park H., & Schaepman-Strub G. (2020) *Extensive fires in southeastern Siberian permafrost linked to preceding Arctic Oscillation*, SCI. ADV. 6(2): 1–7, 2, 4 ("Accumulated positive temperature anomalies in late winter lead to earlier melting in snow cover's seasonal evolution. Once snow cover is reduced, a positive snow-albedo feedback accelerates surface warming and snowmelt (fig. S8). Thus, significant negative snowmelt is observed in March and April as a result (Fig. 3, B and C). Earlier snowmelt leads to faster exposure of the ground surface and litter, which, in turn, allows favorable conditions for fire spreading because this region consists mostly of larch (*Larix gmelinii*) forests with a high amount of litter that can act as fire fuel (*22*)…. This analysis shows a generally negative relation between burned area and P/PET [potential evapotranspiration], meaning that more arid regions have stronger fire activity.").

[480] Schuur E. A. G., *et al*. (2008) *Vulnerability of Permafrost Carbon to Climate Change: Implications for the Global Carbon Cycle*, BIOSCIENCE 58(8): 701–714, 710 ("Model scenarios of fire in Siberia show that extreme fire years can result in approximately 40% greater C emissions because of increased soil organic C consumption (Soja et al. 2004). In combination with dry conditions or increased water infiltration, thawing and fires could, given the right set of circumstances, act together to expose and transfer permafrost C to the atmosphere very rapidly"). *See also* McCarty J. L., Smith T. E. L., & Turetsky M. R. (2020) *Arctic fires re-emerging*, NAT. GEOSCI. 13(10): 658–660, 659 ("Evidence from 2019 and 2020 suggests that extreme temperatures accompanied by drying are increasing the availability of surface fuels in the Arctic. New tundra vegetation types, including dwarf shrubs, sedges, grasses and mosses, as well as surface peats, are becoming vulnerable to burning, and what we typically consider to be 'fire-resistant' ecosystems, such as tundra bogs, fens and marshes, are burning (Fig. 1). While wildfires on permafrost in boreal regions of Siberia are not uncommon[7], 2020's fires are unusual in that more than 50% of the detected fires above 65° N occurred on permafrost with high ice content. Ice-rich permafrost is considered to contain the most carbon-rich soils in the Arctic[8] and burning can accelerate thaw and carbon emission rates[9]").

[481] Thoman R. L., Moon T. A., & Druckenmiller M. L. (2023) *Executive Summary*, *in* ARCTIC REPORT CARD 2023, Thoman R. L., Moon T. A., & Druckenmiller M. L. (eds.), National Oceanic and Atmospheric Administration, 4–5 ("During late summer 2023, northern Canada experienced unprecedented and destructive wildfire. … Based on government reporting, as of late October 2023, wildfire burned 4.61 million hectares (11.39 million acres) in highlatitude North America (Alaska, USA and Yukon Territory and Northwest Territories, Canada). More than 90 percent of the area burned was in the Northwest Territories, where about 300 separate fires burned 4.16 million hectares (10.28 million acres), the largest area burned in 44 years of record (Northwest Territories Department of Environment and Climate Change 2023, see Fig. SB1)."). *See also* Jones M. W., *et al.* (2024) *State of Wildfires 2023–2024*, EARTH SYST. SCI. DATA 16(8): 3601–3685, 3615 ("Record-breaking burned area. The North American boreal forests, particularly in Canada, experienced an unprecedented fire season. The BA reached 6 times the average since 2001. High C emissions. Fire C emissions in Canada were over 9 times the average since 2003, contributing significantly to global C emission totals for the year."); 3635 ("The fire weather conditions in Canada during June 2023 were 2.9–3.6 times more likely due to anthropogenic forcing.").

[482] Byrne B., Liu J., Bowman K. W., Pascolini-Campbell M., Chatterjee A., Pandey S., Miyazaki K., van der Werf G. R., Wunch D., Wennberg P. O., Roehl C. M., & Sinha S. (2024) *Carbon emissions from the 2023 Canadian wildfires*, NATURE 633(8031): 835–839, 835 ("The 2023 Canadian forest fires have been extreme in scale and intensity with more than seven times the average annual area burned compared to the previous four decades1. Here, we quantify the carbon emissions from these fires from May to September 2023 on the basis of inverse modelling of satellite carbon monoxide observations. We find that the magnitude of the carbon emissions is 647 TgC (570–727 TgC), comparable to the annual fossil fuel emissions of large nations, with only India, China and the USA releasing more carbon per year[2].").

[483] Byrne B., Liu J., Bowman K. W., Pascolini-Campbell M., Chatterjee A., Pandey S., Miyazaki K., van der Werf G. R., Wunch D., Wennberg P. O., Roehl C. M., & Sinha S. (2024) *Carbon emissions from the 2023 Canadian wildfires*, NATURE 633(8031): 835–839, 837 ("Next, we examine future climate conditions in the region and how they compare

to the concurrent climate conditions that led to the massive fires. Figure 3 shows the decadal mean temperature and precipitation Z-scores for the median of 27 models from the coupled model intercomparison project phase 6 (CMIP6)[26] under the moderate-warming shared socioeconomic pathway (SSP) 2–4.5 (ref. 4). Large projected temperature increases are found to occur, with average temperatures in the 2050s similar to 2023.").

[484] World Weather Attribution (22 August 2023) *Climate change more than doubled the likelihood of extreme fire weather conditions in Eastern Canada* ("In today's climate, intense fire weather like that observed in May-July 2023 is a moderately extreme event, expected to occur once every 20-25 years. This means in any given year such an event is expected with 4-5% probability. Climate change made the cumulative severity of Québec's 2023 fire season to the end of July around 50% more intense, and seasons of this severity at least seven times more likely to occur. Peak fire weather (FWI7x) like that experienced this year is at least twice as likely, and the intensity has increased by about 20% due to human-induced climate change. Observed changes are typically larger than in the models.").

[485] Holzworth R. H., Brundell J. B., McCarthy M. P., Jacobson A. R., Rodger C. J., & Anderson T. S. (2021) *Lightning in the Arctic*, GEOPHYS. RES. LETT. 48(7): 1–6, 1 ("The ratio of strokes occurring above a given latitude, compared to total global strokes, increases with time, indicating that the Arctic is becoming more influenced by lightning. We compare the increasing fraction of strokes with the NOAA global temperature anomaly, and find that the fraction of strokes above 65°N to total global strokes increases linearly with the temperature anomaly and grew by a factor of 3 as the anomaly increased from 0.65°C to 0.95°C."), *discussed in* DeGeorge K. (5 January 2022) *The high Arctic saw a huge spike in lightning last year,* ARCTICTODAY ("In 2021 there were 7,238 lightning events north of 80 degrees North latitude, the company said. That's almost twice as many as in the preceding nine years combined. Even further north — north of 85 degrees — the company recorded a record high 634 events. (Areas of the Arctic further south, where lightning is a little more common, didn't see such dramatic increases.).").

[486] Chen Y., Romps D. M., Seeley J. T., Veraverbeke S., Riley W. J., Mekonnen Z. A., & Randerson J. T. (2021) *Future increases in Arctic lightning and fire risk for permafrost carbon*, NAT. CLIM. CHANG. 11(5): 404–410, 407–408 ("Lightning-driven increases in fire may trigger a positive fire–vegetation–soil feedback that promotes shrub expansion, northward displacement of the treeline and changes in tree species composition[8,25,51,52]. A dynamic vegetation feedback may develop over a longer timescale than the atmospheric processes that regulate lightning flash rate and fire ignition. … Together, the vegetation dynamics and changes in fire weather may contribute to a higher ratio of burned area to lightning flash rate north of the treeline than what is currently observed (Extended Data Fig. 8a). After we add this amplifying effect from a vegetation feedback into our simple fire model (by assuming that the ratio of burned area to lightning flash rate in the Arctic tundra will change to the present-day value in boreal forests 480 km south of the treeline, referred to as the 'dynamic vegetation' approach), the model predicts a 570 ± 480% enhancement in burned area and carbon release by the end of this century in Arctic tundra. Increases in burned area within Arctic tundra, in turn, may increase the vulnerability of the permafrost carbon reservoir in at least two ways (Fig. 4b). First, more frequent fires have the potential to damage or remove the surface insulating layer of organic matter in areas that have moderate or high fire severity[59]. The loss of this layer through wildfire combustion will expose the underlying permafrost to substantial warming and degradation[s] and lead to thermokarst development in ice-rich permafrost[60]. … Second, with the expansion of shrubs and northern forests in fire-disturbed areas, surface albedo will probably decline in spring and summer, and the extra energy absorbed by the land surface may further amplify regional climate warming[63]. … Extra warming and productivity from a fire-driven northward expansion of forests could thus accelerate permafrost thaw and decomposition in areas not currently affected by fire.").

[487] Scholten R. C., Jandt R., Miller E. A., Rogers B. M., & Veraverbeke S. (2021) *Overwintering fires in boreal forests,* NATURE 593(7859): 399–404, 404 (We estimated that large overwintering fires in Alaska and the Northwest Territories emitted 3.5 (standard deviation, 1.1) Tg of carbon between 2002 and 2018, 64% of which occurred during the 2015 Northwest Territories and 2010 Alaska fire seasons. The contribution of smouldering combustion is generally underestimated in carbon emission estimates from boreal fires. Thus, our estimate is likely to be conservative, because overwintering fires exhibit a substantial smouldering phase and may burn deeper than our emissions model currently predicts. In addition, smouldering fires emit relatively more methane and less carbon dioxide in comparison to flaming fires41, yet methane has a much larger global warming potential.").

[488] Comer B., Olmer N., Mao X., Roy B., & Rutherford D. (2017) *Prevalence of heavy fuel oil and black carbon in Arctic shipping, 2015 to 2025*, International Council on Clean Transportation, 3, 4 ("Studies have analyzed the amount of HFO used and carried in the Arctic. Between 2011 and 2013, Det Norske Veritas completed a series of reports for the AC's Protection of the Arctic Marine Environment (PAME) working group to help it understand the use and carriage of HFO in the Arctic (Det Norske Veritas [DNV], 2011, 2013). In these studies, DNV found that only 20% of vessels sailing in the IMO Arctic from August to November 2010, and 28% from January to December 2012, operated on HFO. However, roughly 78%, or 400,000 tonnes, of the bunker fuel mass on board vessels in the IMO Arctic was HFO. DNV found that fishing vessels dominated the Arctic fleet in terms number of ships, operating hours, and fuel consumption in the Arctic; however, they assumed that most of these vessels operated on lighter and cleaner distillate fuels, rather than HFO, a reasonable assumption according to the results presented here. Bulk carriers, passenger vessels, and oil tankers had the most HFO fuel on board by mass because of their larger bunker tank capacity. A recent International Council on Clean Transportation (ICCT) working paper (Comer, Olmer, & Mao, 2016) found that whereas less than half of ships operating in the IMO Arctic used HFO in 2015, the mass of fuel onboard all ships in the IMO Arctic was dominated by HFO (76% HFO; 23% distillate; less than 1% LNG, nuclear, and gas boil of), because ships operating on HFO tend to be larger ships with large bunker fuel tanks. That paper reported that ships in the IMO Arctic in 2015 had more than 830,000 t of HFO onboard, more than twice the amount estimated by DNV for the year 2012. A portion of this substantial increase in fuel carriage is attributable to greater carriage of HFO; however, the bulk of this diference is likely as a result of having more complete ship position and ship characteristics data in the 2016 ICCT study than in the 2013 DNV study. Comer et al. (2016) found that the carriage of HFO as bunker fuel in the IMO Arctic in 2015 was dominated by bulk carriers (247,800 t), container vessels (112,900 t), oil tankers (110,600 t), general cargo vessels (76,600 t), and fishing vessels (76,200 t). … Several studies have estimated BC emissions in the Arctic, although the geographical definitions of the Arctic are inconsistent across studies. Corbett et al. (2010) estimated that ships operating in the AMSA area1 emitted 0.88 kilotonnes (kt) of BC in 2004,2 growing to 1.20 kt in 2020, 1.50 kt in 2030, and 2.70 kt in 2050 under a BAU scenario. Similarly, Peters et al. (2011) estimated that ships operating within the AMAP boundary emitted 1.15 kt of BC emissions in 2004, growing to 2.16 kt in 2030 and 2.96 kt in 2050. Both studies assumed a BC emission factor (EF) of 0.35 g/kg fuel. Two more recent studies—DNV (2013) and Winther et al. (2014)—better match the geospatial extents of the Arctic found in this report. DNV (2013) estimated that ships operating within the IMO Arctic emitted 0.052 kt of BC in 2012, assuming a BC EF of 0.18 g/kg fuel. Winther et al. (2014) estimated ships operating at or above 58.95°N emitted 1.585 kt of BC in 2012, assuming a BC EF of 0.35 g/kg fuel."). *See also* Anselmi E. (6 April 2020*) A new report shows that more ships are visiting the Arctic*, ARCTICTODAY; ***and*** McVeigh K. (10 April 2022) *'Black carbon' threat to Arctic as sea routes open up with global heating*, THE GUARDIAN.

[489] Berkman P. A., Fiske G. J., Lorenzini D., Young O. R., Pletnikoff K., Grebmeier J. M., Fernandez L. M., Divine L. M., Causey D., Kapsar K. E., & Jorgensen L. L. (2022) *Satellite Record of Pan-Arctic Maritime Ship Traffic*, NOAA Technical Report OAR ARC 22-10 (Table 1).

[490] O'Rourke R., Leggett J. A., Comay L. B., Ramseur J. L., Frittelli J., Sheikh P. A., Keating-Bitonti C., & Tracy B. S. (*updated* 24 March 2022) CHANGES IN THE ARCTIC: BACKGROUND AND ISSUES FOR CONGRESS, Congressional Research Service R41153, 19 ("While there continues to be significant international cooperation on Arctic issues, the emergence of great power competition (also called strategic competition) between the United States, Russia, and China, combined with the increase in human activities in the Arctic resulting from the diminishment of Arctic ice, has introduced elements of competition and tension into the Arctic's geopolitical environment,[77] and the Arctic is viewed by some observers as an arena for geopolitical competition among the three countries.[78]"). *See also* Gricius G. (18 March 2021) *Geopolitical Implications of New Arctic Shipping Lanes*, THE ARCTIC INSTITUTE; ***and*** Spohr K. & Hamilton D. S. (eds.) (2020) THE ARCTIC AND WORLD ORDER, Foreign Policy Institute & Henry A. Kissinger Center for Global Affairs, Johns Hopkins University SAIS: Washington, DC.

[491] Gilbert E. (29 January 2024) *Why 2023 was such an exceptional year for Antarctic sea ice*, CARBON BRIEF ("Antarctic sea ice is a critical puzzle piece in the regional and global climate picture. The frozen continent as a whole acts as the Earth's principal refrigerator, reflecting the sun's energy from its bright, white mirror-like surface, helping keep temperatures cool. Sea ice formation around its coastline acts as an engine for ocean currents and influences weather patterns that can have far-reaching effects."). *See also* (27 March 2024) *Antarctica, Earth's largest*

refrigerator, is defrosting, THE ECONOMIST ("A build-up of jaw-dropping events and extremes in recent years has shown that Antarctica is undergoing massive changes on land, sea and in the atmosphere above. As a result, a new portrait of the continent is emerging which has, so far, received little attention. Polar scientists are warning of a regime shift. … Alarm bells rang loud and clear in the second half of 2023. They began with a second consecutive summer where the expanse of sea ice floating around the continent hit an all-time low—10% lower than it was in 2022, itself a record-setter. … "If Antarctica is starting to behave like the Arctic and losing sea ice, that is a major concern," says Dr Siegert. It would suggest a profound shift for a region that has for millennia helped to keep the rest of Earth cooler than it would otherwise be."); ***and*** Tandon A. (26 March 2024) *Antarctic sea ice 'behaving strangely' as Arctic reaches 'below-average' winter peak*, CARBON BRIEF ("This year marks the third consecutive minimum Antarctic sea ice extent below 2m km^2.").

492 (27 March 2024) *Antarctica, Earth's largest refrigerator, is defrosting*, THE ECONOMIST ("Scientists are still trying to work out how these gobsmacking extremes are related to the continual fluctuations they see in the oceans and atmosphere, and the extent to which climate change is the ultimate culprit for each event or trend. Yet there have been signs of long-term climate-related change in Antarctica since about the turn of the 21st century, when several massive ice shelves collapsed. Ice shelves are floating slabs of ice that form where glaciers on land flow out to sea. In Antarctica there are 15 large ones, each of which hugs a different part of the coastline. In January 1995, the Larsen A ice shelf, which covered 1,500 square kilometres, disintegrated. Seven years later, dramatic satellite images showed the neighbouring Larsen B ice shelf splinter in a matter of weeks. … Collapsing ice shelves, made more fragile from below by warming waters and jostled by more turbulent seas, have hurried things along. Ice sheets, which sit on the Antarctic continent, are connected to the ocean by glaciers that slowly flow towards the water. Ice shelves, which float at the edge of the continent, act like corks that buttress the glaciers behind them."). *See also* Hanna E., et al. (2024) *Short- and long-term variability of the Antarctic and Greenland ice sheets*, NAT. REV. EARTH ENVIRON. 5(3): 193–210, 198–199 ("However, the contribution of melt to the overall mass imbalance of the AIS is expected to increase with climatic warming. Atmospheric warming over the Larsen B Ice Shelf since the Holocene provides a good analogue for the potential implications of such warming for Antarctica's ice shelves more generally. Such warming made Larsen B vulnerable to the presence of liquid water at its surface. Prior to its 2002 collapse, the ice shelf had experienced two decades of progressive surface lake expansion coinciding with regional climatic warming of approximately 2.5 °C during the mid-late twentieth century. The collapse coincided with the drainage of over 2,000 surface lakes, which are suggested to have contributed to the break-up event through ice shelf flexing, weakening and fracturing. The rapid disintegration of Larsen B instigated prolific inland glacier acceleration owing to the loss of buttressing after the collapse of the ice shelf.").

493 Hodnebrog Ø., Myhre G., Jouan C., Andrews T., Forster P. M., Jia H., Loeb N. G., Olivié D. J. L., Paynter D., Quaas J., Raghuraman S. P., & Schulz M. (2024) *Recent reductions in aerosol emissions have increased Earth's energy imbalance*, COMMUN. EARTH ENVIRON. 5(1): 1–9, 4 ("Regional trend analysis shows that the weak trend in SW_{clear} is largely due to all models having the incorrect sign of the trend south of 30°S (Fig. 3d), and more specifically outside the Antarctica (Fig. 4c; Supplementary Fig. 8), presumably related to surface albedo changes. Thus, the global SW_{clear} trend is too weak in the models due to a missing component in the Southern Ocean, possibly a decrease in sea-ice, an issue that was also raised earlier[7] and which should be revisited by initiatives such as CERESMIP[11].").

494 Gilbert E. (29 January 2024) *Why 2023 was such an exceptional year for Antarctic sea ice*, CARBON BRIEF ("Floating ice also acts as a buffer that can protect the exposed edges of the [Antarctic] ice sheet from the destructive action of waves, meaning that it can curb Antarctica's contribution to sea level rise. By influencing the availability of water from the open ocean, it also affects how much snow can fall to replenish the ice sheet's losses."). *See also* Hanna E., *et al.* (2024) *Short- and long-term variability of the Antarctic and Greenland ice sheets*, NAT. REV. EARTH ENVIRON. 5(3): 193–210, 197 ("[S]atellite observations indicate that glacial advance occurs when highly pressurized sea ice or ice mélange (a mix of sea ice and icebergs) is connected to the shelf front or tidewater glaciers, preventing calving through enhanced buttressing and reduced gravitational flow. Sea ice cover also limits how much and how far atmospheric moisture reaches inland in the form of snowfall. … For relatively small and thin ice shelves (including the Antarctic Peninsula's Larsen A and B ice shelves prior to their collapse), short-lived, high-energy ocean waves during times of regional, storm-driven sea ice loss can also occasionally trigger calving events.").

[495] Siegert M. J., Bentley M. J., Atkinson A., Bracegirdle T. J., Convey P., Davies B., Downie R., Hogg A. E., Holmes C., Hughes K. A., Meredith M. P., Ross N., Rumble J., & Wilkinson J. (2023) *Antarctic extreme events*, FRONT. ENVIRON. SCI. 11: 1–15, 2 ("Notably, the most extreme 'heatwave' ever recorded globally occurred over East Antarctica in March 2022 when surface temperature anomalies of up to 38.5° C were observed (Berkeley Earth, 2022)."), *discussed in* Koumoundouros T. (22 August 2023) *Antarctic Extremes Are Now Virtually Assured, With Global Ramifications*, SCIENCE ALERT.

[496] Siegert M. J., Bentley M. J., Atkinson A., Bracegirdle T. J., Convey P., Davies B., Downie R., Hogg A. E., Holmes C., Hughes K. A., Meredith M. P., Ross N., Rumble J., & Wilkinson J. (2023) *Antarctic extreme events*, FRONT. ENVIRON. SCI. 11: 1–15, 2 ("Notably, the most extreme 'heatwave' ever recorded globally occurred over East Antarctica in March 2022 when surface temperature anomalies of up to 38.5° C were observed (Berkeley Earth, 2022). This event was associated with an 'atmospheric river'; a long filament-shaped atmospheric structure that carries abundant moisture across large distances (many hundreds of kilometres), leading to extreme localised heat and precipitation. These atmospheric rivers transport heat and moisture from the subtropics into the heart of the Antarctic continent."), *discussed in* Koumoundouros T. (22 August 2023) *Antarctic Extremes Are Now Virtually Assured, With Global Ramifications*, SCIENCE ALERT.

[497] Gayle D. & Noor D. (1 August 2024) *Antarctic temperatures rise 10C above average in near record heatwave*, THE GUARDIAN ("Ground temperatures across great swathes of the ice sheets of Antarctica have soared an average of 10C above normal over the past month, in what has been described as a near record heatwave. While temperatures remain below zero on the polar land mass, which is shrouded in darkness at this time of year, the depths of southern hemisphere winter, temperatures have reportedly reached 28C above expectations on some days. … Michael Dukes, the director of forecasting at MetDesk, said that while individual daily high temperatures were surprising, far more significant was the average rise over the month. … "In Antarctica generally that kind of warming in the winter and continuing in to summer months can lead to collapsing of the ice sheets."").

[498] Hobbs W., Spence P., Meyer A., Schroeter S., Fraser A. D., Reid P., Tian T. R., Wang Z., Liniger G., Doddridge E. W., & Boyd P. W. (2024) *Observational Evidence for a Regime Shift in Summer Antarctic Sea Ice*, J. CLIM. 37(7): 2263–2275, 2272 ("In the last 15 years, summer Antarctic sea ice variability has been significantly greater than the earlier satellite record. This increased variance is tied to a marked increase in month-to-month sea ice autocorrelation. These changes, along with changes in the spatial variance of Antarctic sea ice shown by Schroeter et al. (2023), are all consistent with theoretical precursors of a transition to a new sea ice state."); ***and*** Gilbert E. (29 January 2024) *Why 2023 was such an exceptional year for Antarctic sea ice*, CARBON BRIEF ("Although current sea ice extent is no longer the lowest on record, conditions are still well below the 1981-2010 average, and this situation may well persist into the 2024 melt season. So, while it is too early to say conclusively that the recent sea-ice lows are the beginning of a regime shift in Antarctic sea ice, it seems inevitable that it will eventually decline in response to human-caused climate change.").

[499] Duspayev A., Flanner M. G., & Riihelä A. (2024) *Earth's Sea Ice Radiative Effect From 1980 to 2023*, GEOPHYS. RES. LETT. 51(14): 1–9, 4 ("The Antarctic situation is quite different, with SIRE [sea ice radiative effect] roughly flat through 2006 and trending stronger (more negative) from 2007 to 2015, followed by a regime shift starting in 2016 that has resulted in seven (or eight in MERRA-AnnVar) of the eight weakest years of SIRE all occurring since 2016 (Figure 2b), and the eight weakest years in combined Arctic + Antarctic SIRE (Figure 2e) all occurring since 2016 under all cloud scenarios. This variability is broadly consistent with reported variations in Antarctic sea ice extent (e.g., Eayrs et al., 2021; Hobbs et al., 2024; Parkinson, 2019; Purich & Doddridge, 2023; Turner et al., 2017) and associated albedo changes (Riihelä et al., 2021)."); 5–6 ("Comparing eight-year means from the beginning (1980–1988, with 1986 excluded) and end (2016–2023) of the timeseries, however, highlights the 2016 regime change in Antarctic sea ice extent, with differences ranging from 0.08 to 0.12 W m 2 (9%–14%) across cloud scenarios, all significant at the 95% level with pooled t-tests.").

[500] National Snow & Ice Data Center (6 March 2025) *Antarctic sea ice minimum hits a near-record low, again* ("On March 1, Antarctic sea ice likely reached its minimum extent of 1.98 million square kilometers (764,000 square miles),

tying for second lowest extent with 2022 and 2024 in the 47-year satellite record. This is the fourth consecutive year that Antarctic sea ice has reached a minimum below 2.0 million square kilometers (772,000 square miles).”).

[501] National Snow & Ice Data Center, *The Sun sets on the Arctic melt season* (*last visited* 21 November 2023) (“Average Antarctic sea ice extent for September was 16.80 million square kilometers (6.49 million square miles), also far below the previous record for the month. Average September sea ice extent was 1.69 million square kilometers (653,000 square miles) below the 1981 to 2010 average extent of 18.49 million square kilometers (7.14 million square miles). More remarkably, it was 880,000 million square kilometers (340,000 square miles) below 1986, the previous lowest September. The extents this year have been far outside anything observed in the 45-year modern satellite record that began in 1979.”).

[502] International Cryosphere Climate Initiative (2024) STATE OF THE CRYOSPHERE 2024: LOST ICE, GLOBAL DAMAGE, 43 (“This trend of unusually low sea ice extent has continued into the Southern Hemisphere winter of 2023 when sea ice is normally expected to recover; by July 2023, 2.77 million km^2 of ice were ‘missing’ compared to average conditions between 1981–2010 — a reduction equivalent to losing an area of ice the size of Argentina. The final maximum, reached on September 10, 2023, was fully 1 million km^2 below the previous record and over 1.5 million km^2 below the 1981–2010 average.[53]”).

[503] Gilbert E. & Holmes C. (2024) *2023’s Antarctic sea ice extent is the lowest on record*, WEATHER 79(2): 46–51, 48, 49 (“The mean value of the standardised anomaly for JJA [June July August] 2023 when compared against the 1981–2010 JJA climatology was −5.86 (‘−5.86 sigma’), with a minimum value of −7.15 reached on 25 July 2023. This translates 2023’s anomalies into a once-in-a-multi-million-year event without accounting for human-caused climate change; that is, extremely rare.”; “[However], the observed trends in sea ice have occurred in a rapidly changing environment, meaning that climate change (and potentially other factors) is already shaping the calculation of the standardised anomaly and that estimations of this type are not useful for quantifying the rarity of such events. Further, the baseline period from which the climatology SIclim is calculated can alter this estimation. As shown in Table 2, using baselines that include more recent years increases the standard deviation of the baseline and so reduces the calculated standardised anomaly, and therefore, the estimated rarity (return period) of the event. This reflects the changes in sea ice that have occurred due to climate change and/ or changes in natural variability over time. In other words, while we can definitely say that 2023’s sea ice conditions were exceptional, it is difficult to say with any certainty exactly how exceptional.”). *See also* Diamond R., Sime L. C., Holmes C. R., & Schroeder D. (2024) *CMIP6 Models Rarely Simulate Antarctic Winter Sea-Ice Anomalies as Large as Observed in 2023*, GEOPHYS. RES. LETT. 51(10): 1–10, 7–8 (“However, we do note from Figure 1b that in the rare instances that an anomaly of magnitude ΔSIEaug23 is simulated in models, it is preceded by ∼5 years of decrease from the mean, and SIE [sea ice extent] after this anomaly take saround a decade to recover to a new, lower, state, suggesting that there is some persistence in the system after such an event. Given that the mean in Figure 1b is taken over models with very different initial sea ice conditions, we do not expect the 0.7 Mkm^2 reduction 10–20 years after such an event to be a prediction of the future state of sea ice over the 2030s–2040s. However, it does indicate that, at least in models, a reduction of ΔSIEaug23 is followed by a transition to a lower sea-ice state, so we may expect to see this over the coming decades. … Furthermore, when these rare anomalies do occur in models, sea ice takes approximately 10 years to recover to a new state, in which SIE is lowered by 0.5–1 Mkm^2 relative to the mean preceding the anomaly. Therefore, as suggested by Purich and Doddridge (2023) and Ionita (2024), 2023's low may indeed act as a bellwether of future change, indicating a transition to a new regime of lowered winter sea ice, at least for the next few decades.”).

[504] Koumoundouros T. (22 August 2023) *Antarctic Extremes Are Now Virtually Assured, With Global Ramifications*, SCIENCE ALERT (“It's the midst of winter in the Southern Hemisphere and Antarctica is missing an obscene amount of ice. “One might think that the huge remote continent of Antarctica with its kilometers-thick ice sheet could withstand extremes brought about by climate change, but this is absolutely not the case,” says University of Leeds glaciologist Anna Hogg. The missing sea ice is currently the size of Greenland, a country that spans nearly 2.2 million square kilometres (836,330 square miles). As a six sigma event, it should only occur once in 7.5 million years. But times are changing. New research led by University of Exeter geophysicist Martin Siegert suggests such extremes are now virtually certain to continue.”), *discussing* Siegert M. J., Bentley M. J., Atkinson A., Bracegirdle T. J., Convey

P., Davies B., Downie R., Hogg A. E., Holmes C., Hughes K. A., Meredith M. P., Ross N., Rumble J., & Wilkinson J. (2023) *Antarctic extreme events*, FRONT. ENVIRON. SCI. 11: 1–15.

[505] National Snow & Ice Data Center (3 October 2024) *2024 Antarctic sea ice maximum extent finishes at second lowest* ("On September 19, 2024, Antarctic sea ice stalled out at an annual maximum extent of 17.16 million square kilometers (6.63 million square miles), the second lowest maximum in the satellite record that began in 1979 (Figure 1a). This year's maximum is 200,000 square kilometers (77,000 square miles) above the previous record low set in 2023. It is 1.55 million square kilometers below (598,000 square miles) below the 1981 to 2010 average Antarctic maximum extent.").

[506] Morton A. (10 September 2024) *'Two incredible extreme events': Antarctic sea ice on cusp of record winter low for second year running*, THE GUARDIAN ("Sea ice surrounding Antarctica is on the cusp of reaching a record winter low for a second year running, continuing an "outrageous" fall in the amount of Southern Ocean that is freezing over. The Antarctic region underwent an abrupt transformation in 2023 as the sea ice cover surrounding the continent crashed for six months straight. In winter, it covered about 1.6m sq km less than the long-term average – an area roughly the size of Britain, France, Germany and Spain combined. … [Dr. Will] Hobbs said it could take decades for Antarctic sea ice to recover from last year's event and by then the long-term impact of global heating would be clear. "There's more and more evidence that [the long-term average of sea ice cover] isn't likely to return," he said.").

[507] Siegert M. J., Bentley M. J., Atkinson A., Bracegirdle T. J., Convey P., Davies B., Downie R., Hogg A. E., Holmes C., Hughes K. A., Meredith M. P., Ross N., Rumble J., & Wilkinson J. (2023) *Antarctic extreme events*, FRONT. ENVIRON. SCI. 11: 1–15, 4 ("Ice shelves fringe three-quarters of Antarctica's coastline, providing buttressing support that stabilises the rate of ice flow from the grounded ice sheet and its contribution to global sea level (Siegert M. J. et al., 2020) (see Figure 2A for an overview of the ice shelf system). Over the past 5 decades, satellites have observed the retreat, thinning and disintegration of Antarctic ice shelves (Paolo et al., 2015), with change concentrated in two key sectors of the continent. On the Antarctic Peninsula, ice shelves have retreated on average over the last 50 years, with large sections of the LarsenA, Larsen-B, and Wilkins ice shelves collapsing catastrophically in 1995, 2002, and 2008, respectively (Figure 2B, C). Following a period of relative stability in the 1990s, the collapse of the Larsen-B Ice Shelf was triggered by widespread meltwater ponding on the ice shelf surface where crevasse hydrofractures caused pressure-driven disintegration of the shelf in a matter of days (Scambos and Hulbe, 2000). In the austral summer of 2019/20 high levels of surface melting were observed across the Antarctic Peninsula. If such events become more frequent in a warming climate further incidences of ice shelf disintegration may occur. In West Antarctica, dynamic imbalance is driven by incursions of warm modified [Circumpolar Deep Water (CDW)] melting the floating ice shelves (see above), with the interannual and long-term variability of ocean temperatures linked to atmospheric forcing associated with the El Niño-Southern Oscillation (ENSO) (Jenkins et al., 2018). Since 2009, major iceberg calving events have occurred across the continent on ten Antarctic ice shelves, including the Larsen-C, Wordie and Wilkins ice shelves on the Peninsula, Thwaites and Pine Island Glaciers in West Antarctica, and Nansen, Mertz, Brunt, Amery and Conger ice shelves in East Antarctica. Recent studies have suggested that a complex link between atmospheric and ocean processes may have a role to play in ice shelf stability and calving. Extreme atmospheric conditions drive strong winds that can affect ocean swell, which may have had a role in triggering recent iceberg calving (Francis et al., 2021) and historical ice shelf collapse (Massom et al., 2018). Whilst iceberg calving is part of the normal process of mass loss, if calving frequency changes over time it can require decades of regrowth to replace the lost ice, and therefore may be an indicator of longer-term change. It is now clear that ice shelves can respond to change over short timescales and that long data records are required to disentangle natural variability from longer term more permanent change."), *discussed in* Koumoundouros T. (22 August 2023) *Antarctic Extremes Are Now Virtually Assured, With Global Ramifications*, SCIENCE ALERT.

[508] McSweeney R. & Tandon A. (10 January 2024) *Analysis: The climate papers most featured in the media in 2023*, CARBON BRIEF ("Specifically, ice-shelf area has decreased on the Antarctic Peninsula (by 6,693km^2) and in west Antarctica (by 5,563km^2), and increased in east Antarctica (by 3,532km^2) and on the large Ross and Ronne-Filchner ice shelves (by 14,028km^2), the paper says. … Specifically, the gains the study identifies in ice-shelf area in east Antarctica do not detract from the risks of retreating ice shelves on other parts of the continent, says Hogg: "The decrease in ice shelf area in west Antarctica is particularly important as this ice shelf area actively 'buttresses' the

flow of ice from the ice sheet behind it, which through ice dynamic processes is one of the reasons why west Antarctica is contributing significantly to present-day sea level rise."), *discussing* Andreasen J. R., Hogg A. E., & Selley H. L. (2023) *Change in Antarctic ice shelf area from 2009 to 2019*, THE CRYOSPHERE 17(5): 2059–2072, 2068 ("Our results show that, over the 11 years from 2009 to 2019, ice shelves in Antarctica gained a modest 0.4 % (or 5305 km^2) of their total ice area (Table 1; Fig. 1). This area gain was dominated by significant 14 028 km^2 (1.5 %) ice shelf area gains on the two largest Antarctic ice shelves, Ronne–Filchner and Ross, and a 3532 km^2 (1.3 %) area gain on the East Antarctic ice shelves. This counteracted the large reduction in ice shelf area on the Antarctic Peninsula, where 7.0 % (−6692.5 km^2) of ice was lost, and West Antarctica, where ice shelves lost 5.5 % (−5563 km^2) of their 2009 area. From 2009 to 2019, our observations show that the WAIS and Antarctic Peninsula (AP) experienced overall cumulative mass loss, whereas the AP, Ross, and Ronne–Filchner saw cumulative ice mass growth (Fig. 4). Ice shelves along the West Antarctic Ice Sheet lost 150.2 Gt yr^{-1} of ice mass, with individual drainage basins including Pine Island, Thwaites, and Abbot contributing the most ice loss. On the Antarctic Peninsula, ice shelves also lost a total mass of 104 Gt yr^{-1} over the last decade, contributing significantly to freshwater input into the ocean.").

[509] Siegert M. J., Bentley M. J., Atkinson A., Bracegirdle T. J., Convey P., Davies B., Downie R., Hogg A. E., Holmes C., Hughes K. A., Meredith M. P., Ross N., Rumble J., & Wilkinson J. (2023) *Antarctic extreme events*, FRONT. ENVIRON. SCI. 11: 1–15, 4 ("Ice shelves fringe three-quarters of Antarctica's coastline, providing buttressing support that stabilises the rate of ice flow from the grounded ice sheet and its contribution to global sea level (Siegert M. J. et al., 2020) (see Figure 2A for an overview of the ice shelf system). Over the past 5 decades, satellites have observed the retreat, thinning and disintegration of Antarctic ice shelves (Paolo et al., 2015), with change concentrated in two key sectors of the continent. On the Antarctic Peninsula, ice shelves have retreated on average over the last 50 years, with large sections of the LarsenA, Larsen-B, and Wilkins ice shelves collapsing catastrophically in 1995, 2002, and 2008, respectively (Figure 2B, C). Following a period of relative stability in the 1990s, the collapse of the Larsen-B Ice Shelf was triggered by widespread meltwater ponding on the ice shelf surface where crevasse hydrofractures caused pressure-driven disintegration of the shelf in a matter of days (Scambos and Hulbe, 2000). In the austral summer of 2019/20 high levels of surface melting were observed across the Antarctic Peninsula. If such events become more frequent in a warming climate further incidences of ice shelf disintegration may occur. In West Antarctica, dynamic imbalance is driven by incursions of warm modified [Circumpolar Deep Water (CDW)] melting the floating ice shelves (see above), with the interannual and long-term variability of ocean temperatures linked to atmospheric forcing associated with the El Niño-Southern Oscillation (ENSO) (Jenkins et al., 2018). Since 2009, major iceberg calving events have occurred across the continent on ten Antarctic ice shelves, including the Larsen-C, Wordie and Wilkins ice shelves on the Peninsula, Thwaites and Pine Island Glaciers in West Antarctica, and Nansen, Mertz, Brunt, Amery and Conger ice shelves in East Antarctica. Recent studies have suggested that a complex link between atmospheric and ocean processes may have a role to play in ice shelf stability and calving. Extreme atmospheric conditions drive strong winds that can affect ocean swell, which may have had a role in triggering recent iceberg calving (Francis et al., 2021) and historical ice shelf collapse (Massom et al., 2018). Whilst iceberg calving is part of the normal process of mass loss, if calving frequency changes over time it can require decades of regrowth to replace the lost ice, and therefore may be an indicator of longer-term change. It is now clear that ice shelves can respond to change over short timescales and that long data records are required to disentangle natural variability from longer term more permanent change."), *discussed in* Koumoundouros T. (22 August 2023) *Antarctic Extremes Are Now Virtually Assured, With Global Ramifications*, SCIENCE ALERT.

[510] Scambos T. & Weeman K. (13 December 2021) *The Threat from Thwaites: The Retreat of Antarctica's Riskiest Glacier*, Cooperative Institute for Research in Environmental Sciences ("The glacier is the size of Florida or Britain and currently contributes four percent of annual global sea level rise. If it does collapse, global sea levels would rise by several feet—putting millions of people living in coastal cities in danger zones for extreme flooding. 'Thwaites is the widest glacier in the world,' said Ted Scambos, a senior research scientist at the Cooperative Institute for Research in Environmental Sciences (CIRES). 'It's doubled its outflow speed within the last 30 years, and the glacier in its entirety holds enough water to raise sea level by over two feet. And it could lead to even more sea-level rise, up to 10 feet, if it draws the surrounding glaciers with it.'"). *See also* Rignot E., Mouginot J., Scheuchl B., van den Broeke M., van Wessem M. J., & Morlighem M. (2019) *Four decades of Antarctic Ice Sheet mass balance from 1979–2017*, PROC. NAT'L. ACAD. SCI. 116(4): 1095–1103, 1096 (Table 1 gives 65 cm sea-level equivalent (SLE) for Thwaites glacier).

[511] Morlighem M., *et al.* (2020) *Deep glacial troughs and stabilizing ridges unveiled beneath the margins of the Antarctic ice sheet*, NAT. GEOSCI. 13: 132–137, 134 ("We do not find major bumps in bed topography upstream of the current grounding line that could stop the grounding line retreat, except for two prominent ridges ~35 and 50 km upstream (red lines, Fig. 2a). Ice sheet numerical models indicate that once the glacier retreats past the second ridge, the retreat of Thwaites Glacier would become unstoppable18,19,20."). *See also* Gilbert E. (3 January 2022) *What Antarctica's 'Doomsday' Glacier Could Mean For The World*, SCIENCE ALERT.

[512] Morlighem M., *et al.* (2020) *Deep glacial troughs and stabilizing ridges unveiled beneath the margins of the Antarctic ice sheet*, NAT. GEOSCI. 13: 132–137, *discussed in* International Thwaites Glacier Collaboration, *Thwaites Glacier Facts* (*last visited* 14 February 2023) ("7. Thwaites Glacier ice loss currently contributes around 4% of all global sea-level rise (assuming 3.5 mm annual sea-level rise) and has the potential to contribute significantly more.").

[513] Hanna E., et al. (2024) *Short- and long-term variability of the Antarctic and Greenland ice sheets*, NAT. REV. EARTH ENVIRON. 5(3): 193–210, 199 ("The grounding lines of the large Thwaites and Pine Island glaciers in the AIS have already retreated by more than 1 km year^{-1} since the 1990s (refs. 85,86). Several glacier and ice sheet and shelf models suggest that these grounding lines could retreat far inland (tens of kilometres or more) of their present-day position in the future[90,92,141], as they did during the mid-Pliocene Warm Period and/or some of the Pleistocene warm interglacials (Fig. 3a).").

[514] Groh A., & Horwath M. (2021) *Antarctic Ice Mass Change Products from GRACE/GRACE-FO Using Tailored Sensitivity Kernels*, REMOTE SENS. 13(9): 1736, 1–25, *discussed in* International Thwaites Glacier Collaboration, *Thwaites Glacier Facts* (*last visited* 13 June 2023) ("10. Since 2000, the glacier has had a net loss of more than 1000 billion tons of ice. … 11. The amount of ice loss has doubled over the last 30 years by Thwaites and its neighbouring glaciers.").

[515] Nilsson J., Gardner A. S., & Paolo F. S. (2022) *Elevation change of the Antarctic Ice Sheet: 1985 to 2020*, EARTH SYST. SCI. DATA. 14(8): 3573–3598, 3573 ("On decadal timescales we find that the large glaciers systems of Pine Island, Thwaites, Smith, and Kohler (basins 21 and 22) have shown relatively stable mass loss since the early parts of the satellite era, with signs of accelerated thinning since 2007–2009 (Fig. 11)."), *discussed in* Jet Propulsion Laboratory (5 September 2022) *Previously Unknown Loss of Antarctic Ice Discovered by NASA – "Antarctica Is Crumbling at Its Edges"*, SCITECHDAILY.

[516] Graham A. G. C., Wåhlin A., Hogan K. A., Nitsche F. O., Heywood K. J., Totten R. L., Smith J. A., Hillenbrand C.-D., Simkins L. M., Anderson J. B., Wellner J. S., & Larter R. D. (2022) *Rapid retreat of Thwaites Glacier in the pre-satellite era*, NAT. GEOSCI. 15: 706–713, 706 ("Understanding the recent history of Thwaites Glacier, and the processes controlling its ongoing retreat, is key to projecting Antarctic contributions to future sea-level rise. Of particular concern is how the glacier grounding zone might evolve over coming decades where it is stabilized by sea-floor bathymetric highs. Here we use geophysical data from an autonomous underwater vehicle deployed at the Thwaites Glacier ice front, to document the ocean-floor imprint of past retreat from a sea-bed promontory. We show patterns of back-stepping sedimentary ridges formed daily by a mechanism of tidal lifting and settling at the grounding line at a time when Thwaites Glacier was more advanced than it is today. Over a duration of 5.5 months, Thwaites grounding zone retreated at a rate of >2.1 km per year—twice the rate observed by satellite at the fastest retreating part of the grounding zone between 2011 and 2019. Our results suggest that sustained pulses of rapid retreat have occurred at Thwaites Glacier in the past two centuries. Similar rapid retreat pulses are likely to occur in the near future when the grounding zone migrates back off stabilizing high points on the sea floor."), *discussed in* University of South Florida (5 September 2022) *Faster in the Past: New seafloor images of West Antarctic Ice Sheet upend understanding of Thwaites Glacier retreat*, SCIENCEDAILY. *See also* Tanner J. (20 May 2024) *Researchers studying 'doomsday glacier' make worrying discovery*, THE HILL ("Using satellites and a technique called radar interferometry to track changes in surface elevation, the team found that the glacier appeared to be lifting several centimeters as pressurized tide water moved below the glacier across many miles, further inland than previously thought. … Warmer seawater working its way under the glacier may help explain the "rapid, past, and present changes in ice sheet mass and the slower changes replicated by ice sheet models," the study noted, adding that the pressurized seawater will create a

"vigorous melt" that will further imperil the glacier. … "It will take many decades, not centuries" for the Thwaites Glacier to fully melt," [lead author] Rignot told USA Today."), *discussing* Rignot E., Ciracì E., Scheuchl B., Tolpekin V., Wollersheim M., & Dow C. (2024) *Widespread seawater intrusions beneath the grounded ice of Thwaites Glacier, West Antarctica*, PROC. NAT'L. ACAD. SCI. 121(22): 1–7.

[517] Gilbert E. (3 January 2022) *What Antarctica's 'Doomsday' Glacier Could Mean For The World*, SCIENCE ALERT ("But scientists have just confirmed that this ice shelf is becoming rapidly destabilized. The eastern ice shelf now has cracks crisscrossing its surface and could collapse within ten years, according to Erin Pettit, a glaciologist at Oregon State University. This work supports research published in 2020 which also noted the development of cracks and crevasses on the Thwaites ice shelf. These indicate that it is being structurally weakened. This damage can have a reinforcing feedback effect because cracking and fracturing can promote further weakening, priming the ice shelf for disintegration."). *See also* Scambos T. & Weeman K. (13 December 2021, *updated* 31 January 2022) *The Threat from Thwaites: The Retreat of Antarctica's Riskiest Glacier*, Cooperative Institute for Research in Environmental Sciences ("Thwaites sits in West Antarctica, flowing across a 120km stretch of frozen coastline. A third of the glacier, along its eastern side, flows more slowly than the rest—it's braced by a floating ice shelf, a floating extension of the glacier that is held in place by an underwater mountain. … Massive factures have formed and are growing as well, accelerating its demise, said Pettit. This floating extension of the Thwaites Glacier will likely survive only a few more years. … The "chain reaction," beginning with the potential collapse of Thwaites' Eastern Ice Shelf would set in motion a long-term process which would eventually result in global sea level rise. While the initial steps of ice shelf collapse, glacier speed-up, and increased ice-cliff failure might happen within a couple of decades, the "2 to 10 feet" of sea level rise will require centuries to unfold—and impacts can still be mitigated depending on how humans respond in coming decades. Risk of multiple feet of sea level rise will not happen this decade (and likely not even in the next few decades)."); *and* Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, REV. GEOPHYS. 6: 1–81, 16 ("The observational record has established the predominant role of ocean-driven subsurface melt at the base of ice shelves, leading to the thinning and retreat of Antarctic ice shelves (Khazendar et al., 2016; Y. Liu et al., 2015; Wouters et al., 2015). Shifts in atmospheric circulation have driven increased intrusions of warm Circumpolar Deep Water (CDW) onto the continental shelf at depths of several hundred meters, promoting the melt of basal ice (Jenkins et al., 2016). As ice shelves also provide a supportive "buttressing" effect that opposes and slows the rate of ice flux to sea, loss of ice shelf mass itself accelerates flow from ice streams and enhances discharge of ice into the ocean (Schoof, 2007). Ocean warming in combination with physical stresses can also drive an ice shelf damage feedback in which crevasses and fractures develop within the ice shelves buttressing outlet glaciers of the AIS, accelerating ice loss and further exacerbating damage (Lhermitte et al., 2020). Patterns of ice loss have been influenced partly by natural tropical variability (Jenkins et al., 2016) but are also driven by anthropogenically forced shifts in regional winds and positive feedbacks from the ungrounding of ice sheets (P. R. Holland et al., 2019).").

[518] Greene C. A., Gardner A. S., Schlegel N. J., & Fraser A. D. (2022) *Antarctic calving loss rivals ice-shelf thinning*, NATURE 609: 948–953, 948 ("Our model results show that among all of the ice shelves in Antarctica, Pine Island and Thwaites have responded the most strongly to reduced buttressing caused by ice-shelf thinning and calving. … We know that ice-shelf thinning tends to occur slowly over time, and can only impact buttressing within a limited range on decadal timescales. By comparison, calving and ice-shelf collapse can occur suddenly, with little warning, and can produce immediate increases in grounding-line flux and sea-level rise."), *discussed in* Jet Propulsion Laboratory (5 September 2022) *Previously Unknown Loss of Antarctic Ice Discovered by NASA – "Antarctica Is Crumbling at Its Edges"*, SCITECHDAILY.

[519] Naughten K. A., Holland P. R., & De Rydt J. (2023) *Unavoidable future increase in West Antarctic ice-shelf melting over the twenty-first century*, NAT. CLIM. CHANG. 13(11): 1222–1228, 1222, 1227 ("We find that rapid ocean warming, at approximately triple the historical rate, is likely committed over the twenty-first century, with widespread increases in ice-shelf melting, including in regions crucial for ice-sheet stability. When internal climate variability is considered, there is no significant difference between mid-range emissions scenarios and the most ambitious targets of the Paris Agreement. These results suggest that mitigation of greenhouse gases now has limited power to prevent ocean warming that could lead to the collapse of the West Antarctic Ice Sheet."; "By combining the maximum future

warming trend in our ensembles (Fig. 2) with historical warming, we find that Amundsen Sea ocean conditions in 2100 could be up to 2 °C warmer than pre-industrial temperatures. For Antarctic water masses, a 2 °C increase is striking.").

[520] Reed B., Green J. A. M., Jenkins A., & Gudmundsson G. H. (2023) *Recent irreversible retreat phase of Pine Island Glacier*, NAT. CLIM. CHANG.: 1–7, 1, 5 ("Here, we use an ice-flow model validated by observational data to show that a rapid PIG [Pine Island Glacier] retreat in the 1970s from a subglacial ridge to an upstream ice plain was self-enhancing and irreversible. The results suggest that by the early 1970s, the retreat of PIG had reached a point beyond which its original position at the ridge could not be recovered, even during subsequent periods of cooler ocean conditions. The irreversible phase ended by the early 1990s after almost 40 km of retreat and 0.34 mm added to global mean sea level, making PIG the main contributor from the Antarctic ice sheet in this period."; "When higher melt rates are applied for an extended period of time, to represent what may have happened during the 1940s El Niño event[26,32], there is a rapid retreat down the retrograde slope facilitated by the merging of upstream cavities. Although we used a simple melt-rate parameterization, the initial behaviour of retreat, the speed at which it progresses and the final ungrounding of a pinning point above the ridge are all comparable with satellite observations and sediment records from the 1940s and 1970s[26,27]. … During the suspected period of rapid retreat from the 1970s to the early 1990s, PIG was responsible for a third of the mass loss from West Antarctica and almost 13% of the overall AIS [Antarctic ice sheet[mass loss[25]. Despite its basin comprising of only 1.5% of the entire ice sheet area, PIG was the largest contributor to sea-level rise from the AIS during those years, adding 0.34 mm in total[25].").

[521] Armstrong McKay D. I., Staal A., Abrams J. F., Winkelmann R., Sakschewski B., Loriani S., Fetzer I., Cornell S. E., Rockström J., & Lenton T. M. (2022) *Exceeding 1.5°C global warming could trigger multiple climate tipping points*, SCIENCE 377(6611): 1–10, 7 ("Current warming is ~1.1°C above preindustrial and even with rapid emission cuts warming will reach ~1.5°C by the 2030s (23). We cannot rule out that WAIS [West Antarctic ice sheet] and GrIS [Greenland ice sheet] tipping points have already been passed (see above) and several other tipping elements have minimum threshold values within the 1.1 to 1.5°C range. Our best estimate thresholds for GrIS, WAIS, REEF, and abrupt permafrost thaw (PFAT) are ~1.5°C although WAIS and GrIS collapse may still be avoidable if GMST returns below 1.5°C within an uncertain overshoot time (likely decades) (94)."). *See also* Intergovernmental Panel on Climate Change (2023) AR6 SYNTHESIS REPORT: CLIMATE CHANGE 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 42 ("Risks associated with large-scale singular events or tipping points, such as ice sheet instability or ecosystem loss from tropical forests, transition to high risk between 1.5°C–2.5°C (*medium confidence*) and to very high risk between 2.5°C–4°C (*low confidence*). The response of biogeochemical cycles to anthropogenic perturbations can be abrupt at regional scales and irreversible on decadal to century time scales (*high confidence*). The probability of crossing uncertain regional thresholds increases with further warming (*high confidence*)."); *and* International Cryosphere Climate Initiative (2023) STATE OF THE CRYOSPHERE REPORT 2023 – TWO DEGREES IS TOO HIGH, 9 ("A new integrated model including the complex interactions between ice sheets, oceans and the atmosphere found that West Antarctica and Greenland will cross irreversible thresholds if global temperatures reach 1.8°C even temporarily, committing these ice sheets to increased ice loss and accelerating sea-level rise for several centuries . Only the very low greenhouse gas emissions scenario, with temperatures peaking around 1.6°C and leveling off below 1.5°C by the end of this century, avoids long-term acceleration of sea-level rise from the Earth's two great ice sheets."), *discussing* Park J.-Y., Schloesser F., Timmermann A., Choudhury D., Lee J.-Y., & Nellikkattil A. B. (2023) *Future sea-level projections with a coupled atmosphere-ocean-ice-sheet model*, NAT. COMMUN. 14(1): 1–11.

[522] DeConto R. M., Pollard D., Alley R. B., Velicogna I., Gasson E., Gomez N., Sadai S., Condron A., Gilford D. M., Ashe E. L., Kopp R. E., Li D., & Dutton A. (2021) *The Paris Climate Agreement and future sea-level rise from Antarctica*, NATURE 593(7857): 83–89, 88 ("We find that without future warming beyond 2020, Antarctica continues to contribute to 21st-century sea-level rise at a rate roughly comparable to today's, producing 5 cm of GMSL (Global Mean Sea Level) rise by 2100 and 1.34 m by 2500 (Fig. 3, Table 1). Simulations initially following the +3 °C pathway, but with subsequent CDR (carbon dioxide reduction/negative emissions) delayed until after 2060, show a sharp jump in the pace of 21st-century sea-level rise (Fig. 3b). Every decade that CDR mitigation is delayed has a substantial long-term consequence on sea level, despite the fast decline in CO_2 and return to cooler temperatures (Fig. 3c). Once

initiated, marine-based ice loss is found to be unstoppable on these timescales in all mitigation scenarios (Fig. 3). The commitment to sustained ice loss is caused mainly by the onset of marine ice instabilities triggered by the loss of ice shelves that cannot recover in a warmer ocean with long thermal memory (Fig. 3c).”). *See also* Kloenne U., Nauels A., Pearson P., DeConto R. M., Findlay H. S., Hugelius G., Robinson A., Rogelj J., Schuur E. A. G., Stroeve J., & Schleussner C.-F. (2023) *Only halving emissions by 2030 can minimize risks of crossing cryosphere thresholds*, NAT. CLIM. CHANG. 13(1): 9–11, 10 (“With further warming, the ice sheets could be at risk of crossing thresholds which lead to accelerated melting rates that cannot be stopped even by halting global warming. This would commit us to rising sea levels for millennia, with severe consequences for vulnerable coastal regions and small islands. Global mean sea level rise could, however, be halved on millennial 68 timescales by limiting peak warming to 1.5°C compared to 2°C.”).

[523] World Meteorological Organization (2023) THE GLOBAL CLIMATE 2011-2020, 20 (“During the 2011-2020 decade, Greenland lost mass at an average rate of 251 Gt yr^{-1} and reached a new record mass loss of 444 Gt in 2019. Antarctica lost ice at an average rate of 143 Gt yr^{-1} during this decade, with more than three-quarters of this mass loss coming from West Antarctica. Compared to the previous decade (2001-2010), this represents an increase of 38 % in ice losses from Greenland and Antarctica combined and confirms the sustained increase of ice sheet mass loss compared to the 1990s (1992-2000), when Greenland and Antarctica ice losses amounted to only 84 Gt yr^{-1}.”).

[524] Armstrong McKay D. I. & Loriani S. (eds.) (2023) *Section 1: Earth systems tipping points*, in GLOBAL TIPPING POINTS REPORT 2023, Lenton T. M., et al. (eds.), 9, 12 (“With about 1.2°C of global warming compared to pre-industrial levels, we are getting dangerously close to the temperature thresholds of some major tipping points for the ice sheets of Greenland and West Antarctica. Crossing these would lock in unavoidable long-term global sea level rise of up to 10 metres.”; “Table 1.2.1: Summary of evidence for tipping dynamics, key drivers and biophysical impacts in each system considered in this chapter” [see column on biophysical impacts for Greenland and West Antarctic ice sheets].). For higher estimates of sea-level rise based on Earth’s past climate, *see* International Cryosphere Climate Initiative (2023) STATE OF THE CRYOSPHERE REPORT 2023 – TWO DEGREES IS TOO HIGH, 12 (“Because of the existence of these thresholds, when temperatures reached 2°C above pre-industrial in the Earth’s past, sea levels peaked at around 12–20 meters higher than present-day levels. During the height of the Pliocene 3 million years ago, when CO_2 levels were comparable to today and temperatures stabilized at 2–3°C higher than pre-industrial, sea levels may have peaked at around 20 meters higher than today’s.[19,20,26,40] Such extensive sea level rise would be catastrophic for today’s coastal communities — yet we are currently on track for even higher temperature peaks than those that drove these past sea level rises.”).

[525] Armstrong McKay D. I. & Loriani S. (eds.) (2023) *Section 1: Earth systems tipping points*, in GLOBAL TIPPING POINTS REPORT 2023, Lenton T. M., et al. (eds.), 101 (“Direct interactions between Greenland and West Antarctic ice sheets via sea level[:] It is known that an increase in sea level has an overall destabilizing influence on marine-based sectors of ice sheets, possibly triggering or enhancing the retreat of their grounding line (Schoof, 2007; Weertman, 1974). In the case of ice sheet collapse, the induced sea level rise would vary locally depending on gravitational effects (with sea level falling near the former ice sheet as less water is attracted towards it), rotational effects, and mantle deformation (Kopp et al., 2010; Mitrovica et al., 2009). Overall, sea level rise is expected to negatively impact both the GrIS and WAIS, but more strongly the latter, where most of the bedrock lies well below sea level (Gomez et al., 2020).”).

[526] Armstrong McKay D. I. & Loriani S. (eds.) (2023) *Section 1: Earth systems tipping points*, in GLOBAL TIPPING POINTS REPORT 2023, Lenton T. M., et al. (eds.), 100 (“The AMOC, Greenland Ice Sheet (GrIS), and West Antarctic Ice Sheet (WAIS) are key tipping systems and are threatened by increasing CO_2 emissions and temperatures (Armstrong McKay et al., 2022; Pörtner et al., 2019). Moreover, GrIS, AMOC, and WAIS interact on very different timescales, ranging from decades to multiple centuries. While some of those links might be stabilising, others are destabilizing and would allow for the possibility of large-scale cascading events.”). *See also* Rosser J. P., Winkelmann R., & Wunderling N. (2024) *Polar ice sheets are decisive contributors to uncertainty in climate tipping projections*, COMMUN. EARTH ENVIRON. 5(1): 1–11, 5–6 (“We initially focus on the GIS as it is consistently one of the most important components in both the Sobol variance analysis (see Figs. 1 and 2) and the leave one out analysis (see Fig. 4), giving one of the biggest decreases in mean number of elements tipped when removed from the 1.5 °C scenario.

At 1.5 °C, the impact of totally removing the GIS is a reduction of 46% in the mean number of elements tipped and components transitioned in the system, but it also has significant impacts on the qualitative behaviour of the system. As the GIS has a low tipping point (between 0.8 and 3.0 °C) and strong links to other tipping elements (AMOC, WAIS), it is a key initiator of cascades at low global warming levels. So, when it is removed, the amount of tipping events and cascading effects that we record in the other components is greatly reduced. … AMOC behaves very differently to the GIS in the model, acting as a mediator of cascades and also as a stabiliser of the GIS in the cases where the AMOC tips due to its strong stabilising link to the GIS. This makes its impact much more nuanced than the GIS as seen in Fig. 4. When the AMOC is removed entirely at 1.5 °C, the mean number of elements tipped and components transitioned is reduced by 37%, less than the 46% when the GIS term was removed. This is because the total removal of the AMOC tipping (and the subsequent loss of Amazon and ENSO tipping, which are only tipping at this temperature due to AMOC forcing) is significantly compensated by increases in the tipping of the GIS and ASSI [Arctic summer sea ice], as they are no longer stabilised by the AMOC. Therefore, removing a component can have both a quantitative impact on the amount of tipping in a system but also a large qualitative impact on the behaviour of different elements and which elements tip. This suggests that if components are missing from an analysis or a climate model, even the broad behaviour of climate components may be incorrectly modelled, and the relative importance of components and regions of the climate system may be misjudged."); *and* Klose A. K., Donges J. F., Feudel U., & Winkelmann R. (2024) *Rate-induced tipping cascades arising from interactions between the Greenland Ice Sheet and the Atlantic Meridional Overturning Circulation*, EARTH SYS. DYNAM. 15: 635–652.

[527] Armstrong McKay D. I. & Loriani S. (eds.) (2023) *Section 1: Earth systems tipping points*, in GLOBAL TIPPING POINTS REPORT 2023, Lenton T. M., et al. (eds.), 18 ("While a recent intercomparison study using three different ice sheet models (Hill et al., 2023) concluded that the current observed retreat of grounding lines in West Antarctica is not yet driven by this instability, mounting evidence from modelling studies (e.g., Reese et al., 2023; Seroussi et al., 2017; Arthern and Williams 2017; Golledge et al., 2021; Garbe et al., 2020) suggests that, unless the current warming trend is reversed to colder conditions in the near future, parts of the WAIS such as the Amundsen basin would be committed to long-term irreversible grounding-line retreat driven by MISI. The loss of the Amundsen basin alone would raise global sea levels by roughly 1.2 metres, (Morlighem et al., 2020). Additional large-scale ice sheet changes in West Antarctica could be triggered in the coming decades in response to projected warming. Due to the long response time of the ice sheet, the respective mass loss would unfold and sea level thus keep rising for centuries to millennia (Golledge et al., 2015; Winkelmann et al., 2015). … Based on these different lines of evidence, there is high confidence that the WAIS is a tipping system, with the potential for widespread, and at least partly irreversible ice loss. Recent estimates of the respective global warming levels at which such tipping dynamics are triggered range from 1°C to 3°C of warming compared to pre-industrial levels (Garbe et al., 2020; Golledge et al., 2017; Reese et al., 2023). This means that the complete decline of the WAIS could be triggered by warming projected under higher-emission scenarios for this century (Chambers et al., 2022; Golledge et al., 2015).").

[528] Naughten K. A., Holland P. R., & De Rydt J. (2023) *Unavoidable future increase in West Antarctic ice-shelf melting over the twenty-first century*, NAT. CLIM. CHANG. 13(11): 1222–1228, 1223–1224 ("Future warming and melting are markedly stronger than historical trends, with ensemble mean future warming trends ranging from 0.8 to 1.4 °C per century (Extended Data Table 1) compared with the historical mean of 0.25 °C per century. Even under the most ambitious mitigation scenario, Paris 1.5 °C, the Amundsen Sea warms three times faster than in the twentieth century. … The Paris 1.5 °C, Paris 2 °C and RCP 4.5 trends are all statistically indistinguishable, assessed in any combination, for both warming and melting. Only RCP 8.5, the most extreme scenario, is distinct from the others. This result suggests that climate mitigation has limited power to prevent ocean warming which controls sea-level rise from the WAIS and that internal climate variability presents a larger source of uncertainty than future greenhouse gas emissions. … Therefore, while mitigation of the worst-case climate change scenario still has the potential to reduce Amundsen Sea warming, it will probably not make a difference for several decades. By this time, the impact on some glacier basins of the WAIS could be irreversible, even if ocean temperatures then returned to present-day values."). *See also* Kloenne U., Nauels A., Pearson P., DeConto R. M., Findlay H. S., Hugelius G., Robinson A., Rogelj J., Schuur E. A. G., Stroeve J., & Schleussner C.-F. (2023) *Only halving emissions by 2030 can minimize risks of crossing cryosphere thresholds*, NAT. CLIM. CHANG. 13(1): 9–11, 10 ("The IPCC assesses that … [f]or Antarctica, there is large uncertainty around potential instabilities, which could trigger significant losses. The threshold for instability of the West Antarctic Ice Sheet (WAIS) might be between 1.5-2°C. Only parts would be lost below 2°C, with complete

or near-complete loss at 2-3°C peak warming. Above 3°C the WAIS will be completely and the East Antarctic Wilkes Subglacial Basin substantially or completely lost over multiple millennia. Large losses from East Antarctica could occur above 5°C.").

[529] International Cryosphere Climate Initiative (2024) STATE OF THE CRYOSPHERE 2024: LOST ICE, GLOBAL DAMAGE, 10 ("Greenland and (parts of) Antarctica have certain thresholds beyond which irreversible melt becomes inevitable and potentially rapid.[2,29,46–48] In Earth's past, several of these thresholds have occurred somewhere between 1 and 2 degrees of warming above pre-industrial: likely about 1°C for the WAIS [West Antarctic ice sheet] and Antarctic Peninsula (containing about 5 meters SLR [sea level rise]); and between 1.5°C and 2°C for Greenland (approximately 7 meters SLR).[2,49] (It should be noted that changes around past thresholds were paced by slow changes in Earth's orbit – unlike today's rapid warming that is driven by greenhouse gas emissions from human activities). Some of the most advanced ocean and ice-sheet models available now suggest that because of ocean warming caused by fossil fuel emissions to date (and the amount locked in for the future), extensive West Antarctic ice shelf melting, including in regions crucial for maintaining ice sheet stability, has now become inevitable. This means that the opportunity to preserve much of the West Antarctic Ice Sheet, with its potential 3.5 meters of sea-level rise, has now probably passed even with very low emissions trajectories.[6,7,32] Its loss can be slowed, but not prevented entirely."). *See also* Armstrong McKay D. I. & Loriani S. (eds.) (2023) *Section 1: Earth systems tipping points*, in GLOBAL TIPPING POINTS REPORT 2023, Lenton T. M., et al. (eds.), 17 ("Substantial ocean warming and ice shelf basal melting is committed in the Amundsen Sea over the 21st Century, which will likely accelerate the retreat of several key WAIS outlet glaciers including the Thwaites and Pine Island glaciers (Naughten et al. 2023)."), *discussing* Naughten K. A., Holland P. R., & De Rydt J. (2023) *Unavoidable future increase in West Antarctic ice-shelf melting over the twenty-first century*, NAT. CLIM. CHANG. 13(11): 1222–1228.

[530] Noël B., van Wessem J. M., Wouters B., Trusel L., Lhermitte S., & van den Broeke M. R. (2023) *Higher Antarctic ice sheet accumulation and surface melt rates revealed at 2 km resolution*, NAT. COMMUN. 14(1): 1–11, 5 ("Integrated over the whole of Antarctica (ANT), melt in the 2 km product increases by 51 Gt year^{-1} (46% for 1979–2021 in Fig. 2d) relative to the 27 km product (black line and grey band in Fig. 2c). The elevation correction contributes 38 Gt year^{-1} (34%) to the total surface melt increase (Supplementary Fig. 1a, b). This effect is particularly important near the grounding line where surface elevation is generally reduced at 2 km, and steep topographic gradients were not accurately captured at 27 km. Over low-lying ice shelves, the combined elevation difference and strong melt gradients locally enhance surface melt at 2 km. Spatial refinement of the ice mask from 27 km to 2 km contributes 10 Gt year^{-1} (9%) to the total melt increase (Supplementary Fig. 1c, d), while the remaining 3 Gt year^{-1} (3%) stem from albedo correction over blue ice areas."); 7 (Applying statistical downscaling to RACMO2.3p2 at 27 km, we show that melt at 2 km increases by 45% to reach 167 ± 32 Gt year^{-1} (black line and grey band in Fig. 2c). Melt mostly increases along the grounding line, in good agreement with in situ AWS [automatic weather station] measurements (Supplementary Fig. 2d, e) and QuikSCAT records (Supplementary Fig. 5). We find that the higher surface melt rates persist in the future irrespective of the warming scenario, both Antarctic-wide and at the sector scale (Fig. 5a, b and Supplementary Fig. 6), suggesting higher future melt rates than previously estimated. While the magnitude of melt increase remains small in the present-day (51 Gt year^{-1} for 1979–2021) (grey band in Fig. 5a), we predict that it could become over 3-fold (170 Gt year^{-1}) to over 10-fold (525 Gt year^{-1}) larger in 2090–2099 under SSP1-2.6 (cyan band) and SSP5-8.5 (red band). Most of the melt increase relative to present-day occurs along the grounding line fringing floating ice shelves, especially over Larsen C and Dronning Maud Land (Fig. 5c–f).").

[531] Noël B., van Wessem J. M., Wouters B., Trusel L., Lhermitte S., & van den Broeke M. R. (2023) *Higher Antarctic ice sheet accumulation and surface melt rates revealed at 2 km resolution*, NAT. COMMUN. 14(1): 1–11, 4 ("Using the 2 km product, we find that the grounded AIS [Antarctic ice sheet] remained in approximate mass balance until the mid-2000s (blue line in Supplementary Fig. 4a), with SMB [surface mass balance] mass gain (2187 ± 107 Gt year^{-1} for 1979–2005) compensating for D [solid ice discharge] mass loss (2187 ± 142 Gt year^{-1}) on average (Fig. 2a), though with large interannual variability. Thereafter, D (2301 ± 142 Gt year^{-1} for 2006–2021) persistently exceeds SMB [surface mass balance] (2168 ± 107 Gt year^{-1}) (Fig.2a), driving the recent mass loss (Supplementary Fig. 4a). We estimate that the grounded AIS has lost 2272 ± 243 Gt of ice since 2002, contributing 6.3 ± 0.7 mm to global sea-level rise (Fig. 3a). The APIS [Antarctic peninsula ice sheet] and WAIS sectors (Fig. 3b, c), contributed 634 ± 61 Gt and 2930 ± 132 Gt to the total mass loss, respectively. In contrast, persistent mass gains in the EAIS sector since 2002

mitigate mass losses from the other two sectors by 1292 ± 158 Gt (Fig. 3d). The climatic signal of the EAIS mass gain remains actively debated.").

[532] Hanna E., et al. (2024) *Short- and long-term variability of the Antarctic and Greenland ice sheets*, NAT. REV. EARTH ENVIRON. 5(3): 193–210, 200 ("The marine geomorphological record has revealed that pulses of extremely rapid grounding-line retreat (between 10 and 600 m day^{-1}) can occur at tidal (sub-daily to daily) timescales in the absence of the steeply retrograde bed topography that is conducive to MISI [marine ice sheet instability]. These pulses of retreat are only sustained for periods of days to months; thus, this behaviour could represent an example of ice sheet perturbation in response to short-term, weather-type forcing. Offshore of the Antarctic Peninsula, marine geomorphological data reveal that a grounding-line retreat rate of up to 50 m day^{-1} (equivalent to ≥10 km year^{-1}) occurred during regional deglaciation of the continental shelf (approximately 10.7 ka) (refs. 79,81,82). This constitutes the highest rate of retreat recorded in Antarctica so far. However, grounding-line retreat rates near this magnitude have recently been detected in West Antarctica by satellites (~30 m day^{-1} over the course of 3.6 months in 2017 at Pope Glacier), offering important corroboration of these past magnitudes of retreat. The long-term ice dynamical response of the AIS to such rapid recession remains unknown. Nonetheless, the prolific rates of retreat inferred from these records imply that, even in the absence of MISI and MICI [marine ice cliff instability], the future pace of short-term AIS retreat over such vulnerable regions could be substantially greater than most satellite-derived and model-derived insights suggest.").

[533] Hanna E., et al. (2024) *Short- and long-term variability of the Antarctic and Greenland ice sheets*, NAT. REV. EARTH ENVIRON. 5(3): 193–210, 199, 200 ("Ultimately, the fate of both [the Larsen B and Wilkins] ice shelves underscores how sustained extreme warm weather events associated with atmospheric river activity, alongside ocean swell wave-induced damage, have the potential to trigger ice shelf disintegration."; "The AIS is not currently in steady state; therefore, short-term variations in atmospheric or oceanic conditions can trigger self-reinforcing (amplifying) feedbacks that increase the sensitivity of the AIS to longer-term climatic forcing.").

[534] King M. D., Howat I. M., Candela S. G., Noh M. J., Jeong S., Noël B. P. Y., van den Broeke M. R., Wouters B., & Negrete A. (2020) *Dynamic ice loss from the Greenland Ice Sheet driven by sustained glacier retreat*, COMM. EARTH & ENV'T.: 1–7, 1 ("The Greenland Ice Sheet is losing mass at accelerated rates in the 21st century, making it the largest single contributor to rising sea levels. Faster flow of outlet glaciers has substantially contributed to this loss, with the cause of speedup, and potential for future change, uncertain.").

[535] Box J. E., Hubbard A., Bahr D. B., Colgan W. T., Fettweis X., Mankoff K. D., Wehrlé A., Noël B., van den Broeke M. R., Wouters B., Bjørk A. A., & Fausto R. S. (2022) *Greenland ice sheet climate disequilibrium and committed sea-level rise*, NAT. CLIM. CHANGE: 808–818, 809, 812 ("Application of the average 2000–2019, hereafter 'recent', climatology to Greenland's entire glacierized area of 1,783,090 km^2 gives an AAR/AAR$_0$ (α) disequilibrium with the current ice configuration corresponding with a 3.3 ± 0.8% committed area and volume loss. Taken in perpetuity, this imbalance with recent climate results in $59 \pm 15 \times 10^3$ km^2 of committed retreat of Greenland's ice area, equivalent to $110 \pm 27 \times 10^3$ km^3 of the ice sheet volume or 274 ± 68 mm of global eustatic SLR [sea level rise]. … Given the breadth and potency of those processes, we contend that known physical mechanisms can deliver most of the committed ice volume loss from Greenland's disequilibrium with its recent climate within this century. Nevertheless, we underscore that a SLR of at least 274 ± 68 mm is already committed, regardless of future climate warming scenarios."), *discussed in* Mooney C. (29 August 2022) *Greenland ice sheet set to raise sea levels by nearly a foot, study finds*, THE WASHINGTON POST; *and* Funes Y. (29 August 2022) *The Greenland Ice Sheet's Terrifying Future*, ATMOS.

[536] Nature Research Briefing (2023) *How rapidly can ice sheets retreat?*, NATURE, 1 ("Our results demonstrate that ice sheets can retreat at up to 600 metres per day — 20 times faster than the highest rate observed in Antarctica by satellites1. Furthermore, our findings reveal the vulnerability of regions of ice sheets with flat beds (those shallower than 1°) to pulses of extremely rapid retreat. Notably, we calculate that present-day rates of ocean-driven melting in Antarctica4 could be sufficient to initiate retreat of tens to hundreds of metres per day across similar bed settings. This includes regions of the vast and potentially unstable Thwaites Glacier in West Antarctica, which, in the past few years, has retreated to within about 4 km of a flat area of its bed. Although the rates of ice-sheet retreat revealed in this study are much higher than those detected so far by satellites, we note that they do not necessarily represent the upper limit

at which retreat can occur. As such, we would not be surprised if similar landforms record even higher rates of retreat in regions that experienced more substantial ice-sheet melting in the past."), *discussing* Batchelor C. L., Christie F. D. W., Ottesen D., Montelli A., Evans J., Dowdeswell E. K., Bjarnadóttir L. R., & Dowdeswell J. A. (2023) [*Rapid, buoyancy-driven ice-sheet retreat of hundreds of metres per day*](), NATURE: 1–6.

[537] Fox-Kemper B., *et al.* (2021) [*Chapter 9: Ocean, Cryosphere and Sea Level Change*](), *in* [CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS](), *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 1308–1309, 1302 ("[T]he main uncertainty related to high-end sea-level rise is "when" rather than "if" it arises: the upper limit of 1.02 m of *likely* sea-level range by 2100 for the SSP 5-8.5 scenario will be exceeded in any future warming scenario on time scales of centuries to millennia (*high confidence*), but it is uncertain how quickly the long-term committed sea level will be reached (Section 9.6.3.5). Hence, global-mean sea level might rise well above the *likely* range before 2100, which is reflected by assessments of ice-sheet contributions based on structured expert judgment (Bamber et al., 2019) leading to a 95th percentile of projected future sea-level rise as high as 2.3 m in 2100 (Section 9.6.3.3) … High-end sea-level rise can therefore occur if one or two processes related to ice-sheet collapse in Antarctica result in an additional sea-level rise at the maximum of their plausible ranges (Sections 9.4.2.5, 9.6.3.3; Table 9.7) or if several of the processes described in this box result in individual contributions to additional sea-level rise at moderate levels. In both cases, global-mean sea-level rise by 2100 would be substantially higher than the assessed *likely* range, as indicated by the projections including *low confidence* processes reaching in 2100 as high as 1.6 m at the 83rd percentile and 2.3 m at the 95th percentile (Section 9.6.3.3). … While ice-sheet processes in whose projection there is *low confidence* have little influence up to 2100 on projections under SSP1-1.9 and SSP1-2.6 (Table 9.9), this is not the case under higher emissions scenarios, where they could lead to GMSL [global mean sea level] rise well above the *likely* range. In particular, under SSP5-8.5, *low confidence* processes could lead to a total GMSL rise of 0.6-1.6 m over this time period (17th-83rd percentile range of p-box including SEJ- and MICI-based projections), with 5th-95th percentile projections extending to 0.5-2.3 m (*low confidence*)."). *See also* Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) [*Mechanisms and Impacts of Earth System Tipping Elements*](), REV. GEOPHYS. 61: 1–81, 19–20 ("As mentioned above, reduction of the GIS will likely require a millennium. Yet the weakening of ice shelf buttressing directly accelerates ice flow and discharge independent of MISI and MICI processes, with immediate implications for observed rates of sea-level rise. Consequently, under our current best understanding, Greenland and Antarctic ice-sheet collapse cannot be considered an abrupt or fast phenomenon in which most sea level impacts manifest within decades. Nevertheless, ice-sheet losses may contribute to regional sea level rise under RCP8.5 and worst-case scenarios that reaches 1–2 m for many cities globally by 2100, seriously threatening existing communities and infrastructure (Trisos et al., 2022). … Although significant uncertainties remain regarding the precise temperature thresholds that could trigger ice-sheet collapse, research to date suggests that aggressive climate mitigation could limit risks from ice-sheet instabilities (Table 4).").

[538] Boers N. & Rypdal M. (2021) [*Critical slowing down suggests that the western Greenland Ice Sheet is close to a tipping point*](), PROC. NAT'L. ACAD. SCI. 118(21): 1–7, 1 ("A crucial nonlinear mechanism for the existence of this tipping point is the positive melt-elevation feedback: Melting reduces ice sheet height, exposing the ice sheet surface to warmer temperatures, which further accelerates melting. We reveal early-warning signals for a forthcoming critical transition from ice-core-derived height reconstructions and infer that the western Greenland Ice Sheet has been losing stability in response to rising temperatures. We show that the melt-elevation feedback is likely to be responsible for the observed destabilization. Our results suggest substantially enhanced melting in the near future."). *See also* Intergovernmental Panel on Climate Change (2023) [AR6 SYNTHESIS REPORT: CLIMATE CHANGE 2023](), *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 42 ("Sea level rise is unavoidable for centuries to millennia due to continuing deep ocean warming and ice sheet melt, and sea levels will remain elevated for thousands of years (*high confidence*).").

[539] Armstrong McKay D. I. & Loriani S. (eds.) (2023) [*Section 1: Earth systems tipping points*](), in [GLOBAL TIPPING POINTS REPORT 2023](), Lenton T. M., et al. (eds.), 16 ("Current estimates for a critical threshold for the GrIS range from 0.8°C to 3°C of warming relative to pre-industrial levels, with a best estimate of about 1.5°C (Robinson et al.,

2012; van Breedam et al., 2020; Noël et al., 2021; Höning et al., 2023). This is supported by palaeorecords which indicate that GrIS had at least partially retreated during the MIS-5 interglacial, and likely collapsed during MIS-11, which was 1-2°C warmer than pre-industrial (Christ et al., 2021). At lower warming levels, simulations with a coupled ice sheet atmosphere model indicate that additional atmospheric dynamic changes in precipitation patterns can restabilise the ice sheet, but above 2°C warming, positive/amplifying feedbacks leading to loss of the majority of the ice sheet cannot be overcome (Gregory et al., 2020)."). For earlier research that placed this tipping point at 1.6 ºC, *see* Overland J., Dunlea E., Box J. E., Corell R., Forsius M., Kattsov V., Olsen M. S., Pawlak J., Reiersen L.-O., & Wang M. (2019) *The urgency of Arctic change*, POLAR SCI. 21: 6–13, 9 ("The summer air temperature "viability threshold" that triggers irreversible wastage of the Greenland ice sheet was previously estimated to be for an annual global temperature increase of 2–5 °C (Gregory and Huybrechts, 2006; Huybrechts et al., 2011). An updated estimate based on a higher resolution simulation that explicitly incorporates albedo and elevation feedbacks suggests a lower loss threshold: 0.8–3.2°C (95% confidence range) (Robinson et al., 2012) with 1.6 °C above pre-industrial conditions as a best estimate. It is likely that the Greenland ice sheet enters a phase of irreversible loss under the RCP 4.5 scenario.").

[540] Trusel L. D., Das S. B., Osman M. B., Evans M. J., Smith B. E., Fettweis X., McConnell J. R., Noël B. P. Y., & van den Broeke M. R. (2018) *Nonlinear rise in Greenland runoff in response to post-industrial Arctic warming*, NATURE 564: 104–108, 104 ("Our results show a pronounced 250% to 575% increase in melt intensity over the last 20 years, relative to a pre-industrial baseline period (eighteenth century) for cores NU and CWG, respectively (Fig. 2). Furthermore, the most recent decade contained in the cores (2004– 2013) experienced a more sustained and greater magnitude of melt than any other 10-year period in the ice-core records. For GrIS cores, 2012 melt is unambiguously the strongest melt season on record. Both NU and CWG annual ice-core-derived melt records significantly ($P < 0.01$) correlate with one another over their 339 years of overlap, and both also with summer air temperatures from the Ilulissat region (Extended Data Table 2; Methods), relationships that improve after applying a 5-year moving average, probably reflecting the noise inherent to melt records owing to variability in meltwater percolation and refreezing. These empirically derived results revealing coherence between independent melt and temperature records emphasize broad-scale GrIS melt forcing, and suggest that summer warming (see Fig. 2) is an important component of the observed regional melt intensification."). *See also* Otosaka I. N., Horwath M., Mottram R., & Nowicki S. (2023) *Mass Balances of the Antarctic and Greenland Ice Sheets Monitored from Space*, SURV. GEOPHYS. 44(5): 1615–1652, 1637 ("Since then [the 1990s], ice losses have accelerated due to increased ice flow of marine terminating glaciers and increased meltwater runoff, rising from 35±29 Gt year^{-1} in the 1990s to 257±42 between 2017 and 2020 (Otosaka et al. 2023) leading to widespread thinning at the ice sheet margins (McMillan et al. 2016). Ice losses from reduced SMB and increased solid ice discharge to the oceans contributed equally to total ice losses over the period 1992–2018. However, this partitioning of Greenland's mass loss has changed over time. In the early 2000s, ice discharge rose sharply primarily driven by the acceleration of outlet glaciers in northwest and southeast Greenland (Moon et al. 2012). However, after 2009 the main driver of Greenland's ice losses was the decrease in SMB [surface mass balance], which accounted for 84% of the increase in mass loss, due to increased surface meltwater runoff (Enderlin et al. 2014).").

[541] Otosaka I. N., Horwath M., Mottram R., & Nowicki S. (2023) *Mass Balances of the Antarctic and Greenland Ice Sheets Monitored from Space*, SURV. GEOPHYS. 44(5): 1615–1652, 1623 ("[I]n recent years, Greenland's mass loss has been dominated by reduced SMB [surface mass balance] as surface melt has intensified since the 2000s (Hanna et al. 2020) from a change in atmospheric circulation pattern favouring more frequent blocking events (Delhasse et al. 2018), leading to increased meltwater runoff. Both ice dynamics and SMB processes will remain important drivers of future Greenland's mass loss with SMB predicted to decrease—and could even become negative around 2055 in a high-end warming scenario, with snowfall accumulation during winter no longer compensating for meltwater runoff in summer (Noël et al. 2021)—and marine terminating glaciers predicted to retreat further inland, especially in northwest and central west Greenland (Choi et al. 2021)."; "For the Greenland Ice Sheet, the IPCC AR6 projected contribution to global mean sea-level rise until 2100 ranges from 0.01 to 0.1 m under a low emission scenario (SSP1-2.6) to 0.09–0.18 m under a high emission scenario (SSP5-8.5). On the other hand, the Antarctic Ice Sheet will likely contribute between 0.03 and 0.27 m under a low emissions scenario and 0.03–0.34 m under a high emission scenario by 2100 based on the IPCC AR6 projections. Beyond 2100, the two ice sheets will continue to lose mass, with greater contribution to global mean sea level projected under high emission scenarios than low emission scenarios. The future evolution of the two ice sheets depends heavily on their local conditions and how a warming climate translates into

changing atmospheric and oceanic conditions. In a warmer world, surface melt due to a warmer atmosphere will dominate ice loss from the Greenland Ice Sheet (Edwards et al. 2021; Goelzer et al. 2020; Payne et al. 2021).").

[542] Larocca L. J., Twining–Ward M., Axford Y., Schweinsberg A. D., Larsen S. H., Westergaard–Nielsen A., Luetzenburg G., Briner J. P., Kjeldsen K. K., & Bjørk A. A. (2023) *Greenland-wide accelerated retreat of peripheral glaciers in the twenty-first century*, NAT. CLIM. CHANGE: 1–5, 1–2 ("Peripheral glaciers and ice caps (GICs) that are distinct from the Greenland Ice Sheet constitute just ~4% of Greenland's total glaciated area but contribute a disproportionally large portion (~14%) of the island's current ice loss. … Over the full ~130 years of observation, Greenland's land-terminating GICs have undergone substantial and widespread retreat (Supplementary Table 1). However, the acceleration in recession in the twenty-first century stands out as distinct and suggests that response to recent warming has been ubiquitous despite the range of climates and GIC characteristics across Greenland. Across all eight regions, the mean frontal change rate (M) during the twenty-first century (~2000–2022: M = −14.8 ± 5.4 m per year) is roughly double that of the twentieth century (~1890–1999: M = −7.7 ± 5.1 m per year; Welch two-sample t-test, t(39) = −4.65, P < 0.001; Fig. 1).").

[543] Millan R., Jager E., Mouginot J., Wood M. H., Larsen S. H., Mathiot P., Jourdain N. C., & Bjørk A. (2023) *Rapid disintegration and weakening of ice shelves in North Greenland*, NAT. COMMUN. 14(1): 1–10, 3 ("Overall, the volume of ice shelves in North Greenland decreased from 957.0 ± 8.5 km^3 in 2000 to 704.0 ± 7.8 km^3 in 2012, equivalent to a loss of 26%. Between 2013 and 2022, the total volume stabilized and slightly increased to 750 ± 7.7 km^3, because of widespread GL [grounding line] retreat and the frontal advance of Petermann, which increased the ice shelf area. Using an historical DEM20, we calculate a total volume of 1149.5 ± 55.1 km3 in 1978. We conclude that ice shelves of North Greenland have lost 35% of their volume during the last 45 years (Fig. S16). Similarly, the total area of floating ice dropped from 5386.6 km^2 in 1978, down to 3305.8 km2 in 2013–2022, hence losing more than onethird of its original extent (Fig. S16).").

[544] Millan R., Jager E., Mouginot J., Wood M. H., Larsen S. H., Mathiot P., Jourdain N. C., & Bjørk A. (2023) *Rapid disintegration and weakening of ice shelves in North Greenland*, NAT. COMMUN. 14(1): 1–10, 5–6 ("Our results document a holistic overview of glacier-climate-ocean interaction in North Greenland. We are able to identify a widespread ongoing phase of weakening for the last remaining ice shelves of this sector. The GL [grounding line] are exposed to the warmest water layers and currently this makes them extremely vulnerable to unstable retreat and ice shelf collapse if ocean thermal forcing continues to rise, which is likely to be the case in the coming century. A loss in the buttressing provided by ice shelves in this sector will likely trigger an increase in the discharge that could rival the largest contributors to Greenland ice mass loss. This could have dramatic consequences in terms of SLR, as it is the sector in Greenland with the greatest SLR potential (2.1 m).").

[545] World Meteorological Organization (2024) STATE OF THE GLOBAL CLIMATE 2023, 13 ("It was the warmest summer on record (1987-present) at the Summit station, 3.4 °C warmer than the 1991–2020 average and 1.0 °C warmer than the previous record.44 Summit station experienced melting conditions for the fifth year on record (2012, 2019, 2021, 2022, 2023); ice core records indicate that significant, melting conditions last happened in the late nineteenth century.").

[546] Ramirez R. (30 July 2021) *The amount of Greenland ice that melted on Tuesday could cover Florida in 2 inches of water*, CNN ("Greenland is experiencing its most significant melting event of the year as temperatures in the Arctic surge. The amount of ice that melted on Tuesday alone would be enough to cover the entire state of Florida in two inches of water.").

[547] National Snow & Ice Data Center (18 August 2021) *Rain at the summit of Greenland*, GREENLAND ICE SHEET TODAY ("On August 14, 2021, rain was observed at the highest point on the Greenland Ice Sheet for several hours, and air temperatures remained above freezing for about nine hours. This was the third time in less than a decade, and the latest date in the year on record, that the National Science Foundation's Summit Station had above-freezing temperatures and wet snow. There is no previous report of rainfall at this location (72.58°N 38.46°W), which reaches 3,216 meters (10,551 feet) in elevation.").

[548] International Cryosphere Climate Initiative (2023) STATE OF THE CRYOSPHERE REPORT 2023 – TWO DEGREES IS TOO HIGH, 12–13 ("Rainfall on the Greenland Ice Sheet has increased by 33% since 1991, and the frequency of extreme deluges is increasing. These deluges drain quickly into the ice sheet through vast networks of micro-cracks that may run hundreds of meters deep, carrying warm surface water to the interior of the ice sheet where it heats the ice internally, melting the ice sheet from within.").

[549] Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, REV. GEOPHYS. 61: 1–81, 18 ("Local annual mean warming of 3°C could be attained this century and would eliminate nearly all Greenland glaciers, raising seas by 7 m over approximately 1,000 years (Gregory et al., 2004; Huybrechts et al., 1991).").

[550] Robinson A., Calov R., & Ganopolski A. (2012) *Multistability and critical thresholds of the Greenland ice sheet*, NAT. CLIM. CHANGE 2(6): 429–432, 429 ("Recent studies have focused on the short-term contribution of the Greenland ice sheet to sea-level rise, yet little is known about its long-term stability. The present best estimate of the threshold in global temperature rise leading to complete melting of the ice sheet is 3.1 ºC (1.9–5.1 ºC, 95% confidence interval) above the preindustrial climate, determined as the temperature for which the modelled surface mass balance of the present-day ice sheet turns negative. Here, using a fully coupled model, we show that this criterion systematically overestimates the temperature threshold and that the Greenland ice sheet is more sensitive to long-term climate change than previously thought. We estimate that the warming threshold leading to a monostable, essentially ice-free state is in the range of 0.8–3.2 ºC, with a best estimate of 1.6 ºC. By testing the ice sheet's ability to regrow after partial mass loss, we find that at least one intermediate equilibrium state is possible, though for sufficiently high initial temperature anomalies, total loss of the ice sheet becomes irreversible. Crossing the threshold alone does not imply rapid melting (for temperatures near the threshold, complete melting takes tens of millennia). However, the timescale of melt depends strongly on the magnitude and duration of the temperature overshoot above this critical threshold."). A modeling study that investigated atmospheric (but not oceanic) forcing concluded that the rate of CO_2 emissions, in addition to total emissions, impacts the Greenland ice sheet's mass loss; *see* Höning D., Willeit M., Calov R., Klemann V., Bagge M., & Ganopolski A. (2023) *Multistability and Transient Response of the Greenland Ice Sheet to Anthropogenic* CO_2 *Emissions*, GEOPHYS. RES. LETT. 50(6): 1–11, 7 ("Whereas the first several centuries of temperature anomaly and of mass loss of the GIS will be affected by the specific shape of the emission pulse, on a Kyr timescale, mass loss of the GIS is mainly controlled by the cumulative CO_2 emission (e.g., Charbit et al., 2008). In Figure 4, we compare the constant emission rate throughout 100 years as used in our study with a potentially more realistic bell-shaped emission rate. As expected, after approximately 1 Kyr, the effect of the specific emission shape on the volume of the GIS is negligible.").

[551] Armstrong McKay D. I. & Loriani S. (eds.) (2023) *Section 1: Earth systems tipping points*, in GLOBAL TIPPING POINTS REPORT 2023, Lenton T. M., et al. (eds.), 16 ("Slow-onset tipping processes such as ice sheet collapse might also be able to withstand a short period of temperature overshoot if the overshoot time is short compared to the effective timescale of the tipping system (Ritchie et al., 2021). For ice sheets this overshoot time could be in the order of decades to centuries (Ritchie et al., 2021; Bochow et al.,2023), which might for example theoretically allow global warming to overshoot a tipping threshold of 1.5°C and return below it by 2100 without triggering ice sheet collapse (Armstrong McKay et al., 2022). However, such overshoot times are very uncertain, and given the distinct challenges of reducing global temperatures over short time horizons, this possibility should not be relied upon in policy.").

[552] Bochow N., Poltronieri A., Robinson A., Montoya M., Rypdal M., & Boers N. (2023) *Overshooting the critical threshold for the Greenland ice sheet*, NATURE 622(7983): 528–536, 528, 530 ("Our results show that the maximum GMT and the time span of overshooting given GMT [global mean temperature] targets are critical in determining GrIS stability. We find a threshold GMT between 1.7 °C and 2.3 °C above preindustrial levels for an abrupt ice-sheet loss. GrIS loss can be substantially mitigated, even for maximum GMTs of 6 °C or more above preindustrial levels, if the GMT is subsequently reduced to less than 1.5 °C above preindustrial levels within a few centuries. However, our results also show that even temporarily overshooting the temperature threshold, without a transition to a new ice-sheet state, still leads to a peak in SLR of up to several metres.").

[553] Bochow N., Poltronieri A., Robinson A., Montoya M., Rypdal M., & Boers N. (2023) *Overshooting the critical threshold for the Greenland ice sheet*, NATURE 622(7983): 528–536, 530 ("A reduction in temperature from ad 2100 to ad 2200 leads to a mitigation of the ice loss, depending on the convergence temperature reached (Fig. 2). Regardless of the peak temperature in ad 2100, a convergence temperature increase of 1.5 °C GMT [global mean temperature] above preindustrial (ΔT_{JJA} = 1.3 °C) by ad 2200 or lower leads to a stable ice sheet, with the equivalent of less than 1 m long-term SLR contribution in simulations with both models (Fig. 2a,b). However, the maximum interim SLR contribution with PISM-dEBM slightly exceeds 1 m for 1.5 °C GMT above preindustrial (Extended Data Fig. 3). For convergence temperatures ΔT_{JJA} > 2.2 °C for PISM-dEBM and ΔT_{JJA} > 1.4 °C for Yelmo-REMBO, the ice sheet is completely lost, regardless of the overshoot temperature in the year ad 2100.").

[554] Klose A. K., Donges J. F., Feudel U., & Winkelmann R. (2024) *Rate-induced tipping cascades arising from interactions between the Greenland Ice Sheet and the Atlantic Meridional Overturning Circulation*, EARTH SYS. DYNAM. 15: 635–652, 645 ("Decreasing the surface mass balance emulating a warming climate beyond its effective threshold a (2) 0dgc may not allow for a GIS stabilization (Fig. 4a and b). Instead, for an AMOC residing sufficiently close to its hosing threshold HHopf, a GIS deglaciation and tipping of the AMOC to the "off" state are detected (trajectory for H = 0.205 Sv in Fig. 4a and corresponding grey area in Fig. 4c). Given a lower freshwater hosing, the AMOC remains in its "on" state with the deglaciation of the Greenland Ice Sheet (trajectory for H = 0.16 Sv in Fig. 4b and corresponding dashed grey area in Fig. 4c). Hence, for a strong surface mass balance decrease, the potential dynamic regimes with Greenland becoming ice-free as well as a strong or a collapsed AMOC depending on the hosing (Fig. 4c) are comparable to the dynamics detected when neglecting the negative feedback (Fig. 3). … Accompanied by a temporary overshoot of its critical threshold by the freshwater flux from a deglaciation of the Greenland Ice Sheet, the AMOC may undergo a critical transition in an overshoot/bifurcation cascade."). *See also* Greene C. A., Gardner A. S., Wood M., & Cuzzone J. K. (2024) *Ubiquitous acceleration in Greenland Ice Sheet calving from 1985 to 2022*, NATURE 625: 523–528, 527 ("The addition of more than 1,000 Gt of freshwater to the North Atlantic Ocean since 1985 provides a buoyancy force that could strengthen the coastal currents of Greenland[32,33], change the course of future iceocean interactions[34,35] and weaken the Atlantic Meridional Overturning Circulation (AMOC)[36–38]. The out-of-balance anomalies we report are modest in comparison with the approximately 500 Gt of ice that flows from the GrIS each year1,[27], but there is some concern that any small source of freshwater may serve as a 'tipping point'[39] that could trigger a full-scale collapse of the AMOC[40,41], disrupting global weather patterns[42,43], ecosystems[44,45] and global food security[46,47]; yet, freshwater from the glacier retreat of Greenland is not included in oceanographic models[48,49] or estimates of state[50] at present. The energy required to melt more than 1,000 Gt of ice is notable (>3,340 exajoules), yet this heat sink is not accounted for in the present Earth energy budgets that are essential for understanding the full scope of global warming[51].").

[555] For recent updates to the observational AMOC record, *see* Henson B. (10 December 2024) *Atlantic circulation collapse? New clues on the fate of a crucial conveyor belt*, YALE CLIMATE CONNECTIONS ("Once corrected and recalibrated, the cable data were in much closer agreement with the other platforms, showing no significant change in the Florida Current during the past 40 years of measurements. And because the Florida Current is such a large part of AMOC, the corrected data cuts the observed decline from 2004 to 2022 in total AMOC transport almost in half, from an original drop of about 14% to a revised drop of about 8%. The authors – led by Denis Volkov at NOAA/University of Miami Cooperative Institute for Marine and Atmospheric Studies – found the revised 8% drop to be only marginally significant. "We have not heard yet from modelers, but I do not think our revised result strongly affects their conclusions, because they deal with much longer timescales compared to the period of observations," Volkov said in an email."), *discussing* Volkov D. L., Smith R. H., Garcia R. F., Smeed D. A., Moat B. I., Johns W. E., & Baringer M. O. (2024) *Florida Current transport observations reveal four decades of steady state*, NAT. COMMUN. 15(1): 1–12. *See also* Rahmstorf S. (2024) *Is the Atlantic Overturning Circulation Approaching a Tipping Point?*, OCEANOG.: 1–14, 6–7 ("Also, analysis of climate models, in which AMOC changes are known, shows that the AMOC strength correlates closely with the cold blob temperature change (Caesar et al., 2018). This result confirms that on longer timescales, the AMOC is the dominant factor, allowing the conclusion that the cold blob so far corresponds to about 15% weakening of the AMOC. The cold blob is not just a surface phenomenon; it is also clearly visible (Figure 8) in the trend of ocean heat content of the upper 2,000 m (Cheng et al., 2022)."); 8 ("Yet more evidence comes from analysis of seawater density in the upper 1,000 m in the subpolar gyre region, which correlates closely with the AMOC

and shows a decline over the past 70 years. This decline implies an AMOC weakening of ~13% over this period (Chafik et al., 2022), consistent with the 15% weakening suggested by the cold blob data.").

[556] Smeed D. A., Josey S. A., Beaulieu C., Johns W. E., Moat B. I., Frajka-Williams E., Rayner D., Meinen C. S., Baringer M. O., Bryden H. L., & McCarthy G. D. (2018) *The North Atlantic Ocean Is in a State of Reduced Overturning*, GEOPHYS. RES. LETT. 45(3): 1527–1533, 1527 ("Using data from an array of instruments that span the Atlantic at 26°N, we show that the AMOC has been in a state of reduced overturning since 2008 as compared to 2004–2008. This change of AMOC state is concurrent with other changes in the North Atlantic such as a northward shift and broadening of the Gulf Stream and altered patterns of heat content and sea surface temperature. These changes resemble the response to a declining AMOC predicted by coupled climate models.").

[557] Boers N. (2021) *Observation-based early-warning signals for a collapse of the Atlantic Meridional Overturning Circulation*, NAT. CLIM. CHANGE 11(8): 680–688, 687 ("The results presented here hence show that the recently discovered AMOC decline during the last decades is not just a fluctuation related to low-frequency climate variability or a linear response to increasing temperatures. Rather, the presented findings suggest that this decline may be associated with an almost complete loss of stability of the AMOC over the course of the last century, and that the AMOC could be close to a critical transition to its weak circulation mode."). *See also* Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, REV. GEOPHYS. 61: 1–81, 5, 7, 8 ("Model simulations of the abovementioned paleoclimate changes indicate that the AMOC may have transitioned rapidly between different modes during past climates, including potentially bistable behaviors. Driven by the salt-advection feedback (Stommel, 1961), the AMOC could switch between "on" and "off" states under natural perturbations such as deglacial meltwater pulses when the ocean system passes certain tipping points.…The AMOC also may have shifted between different modes during Dansgaard-Oeschger events in response to changes in freshwater forcing, rapidly transitioning to a marginally unstable "warm" mode associated with a northward shift of the deep-water formation site and more intense convection, in contrast to flip-ping between an "on" and "off" state (Ganopolski & Rahmstorf, 2001). Moreover, based on an AMOC stability indicator (de Vries & Weber, 2005; W. Liu & Liu, 2013; Rahmstorf, 1996), analyses of modern observations suggest that the current AMOC resides in a bi-stable regime. The circulation may be at risk of an eventual collapse under future anthropogenic warming, as the possibility of an AMOC collapse could be downplayed currently by most coupled climate models due largely to a ubiquitous model bias toward AMOC stability (W. Liu et al., 2014, 2017). … Troublingly, defining particular critical temperature thresholds expected to contribute to committed weakening of the overturning circulation also represents a challenge (Weijer et al., 2019). Hoegh-Guldberg et al. (2018) determined a higher likelihood of more intense weakening for >2°C of warming based on model predictions. Committed loss of the GIS is more likely than not to occur beyond a 2°C warming threshold (Pattyn et al., 2018), with the IPCC expressing *medium confidence* regarding long-term near-complete loss of Greenland ice for sustained warming of 3°C or more (IPCC, 2021). As loss of significant volumes of Greenland ice carries important implications for buoyancy dynamics in deep water formation regions, the IPCC's assessment of a 2°C threshold seems a plausible lower bound above which the risks of significant weakening of the AMOC increase. … Taken together, the possibility that the overturning circulation is currently weakening and may weaken further with continuing warming is sufficiently backed by recent research to justify the degree of past and ongoing attention devoted to this potential tipping element.").

[558] Golledge N. R., Keller E. D., Gomez N., Naughten K. A., Bernales J., Trusel L. D., & Edwards T. L. (2019) *Global environmental consequences of twenty-first-century ice-sheet melt*, NATURE 566(7742): 65–72, 66 ("We introduce annual transient freshwater fluxes from our simulated ice sheets into the climate simulations from 2000-2100 CE under RCP 4.5 and 8.5 conditions. Time-evolving fluxes are calculated by assuming all mass changes in the ice sheet result in a net flux of freshwater to the proximal ocean, which by 2100 CE reach maxima of approximately 0.042 and 0.015 Sv for Antarctica and Greenland respectively for RCP 4.5, and 0.160 and 0.018 Sv for Antarctica and Greenland respectively under RCP 8.5."); 68–69 ("In our experiments a gradual slowing in the first half of the century steepens after 2050, leading to a reduction in AMOC strength of 3 to 4 Sv (approximately 15%) over 50 years. This occurs purely as a consequence of the imposed meltwater fluxes and so would presumably add to any weakening from future climate forcing. The lower (counter-clockwise) cell of the AMOC is weaker and responds more slowly, with changes in this instance being forced primarily by Antarctic meltwater (Figure 5b). Since current climate models are thought

to overestimate the stability of the AMOC, it is possible that future ice-sheet meltwater fluxes may play an even more important role than we predict here.").

[559] Rahmstorf S. (2024) *Is the Atlantic Overturning Circulation Approaching a Tipping Point?*, OCEANOG.: 1–14, 3 ("In other words, the AMOC flows because the northern Atlantic is salty, and it's salty because the AMOC flows. Chicken and egg, or in more technical terms, a self-sustaining feedback effect. This works the other way around as well: If the northern Atlantic becomes less salty because of an inflow of freshwater (rain or meltwater), the water becomes less dense and the AMOC slows down. Thus, it brings less salt to the region, which slows the AMOC further. This process is called the salt transport feedback. Beyond a critical threshold, it becomes a self-amplifying vicious circle, and the AMOC grinds to a halt. That threshold is the AMOC tipping point (called Stommel Bifurcation in Figure 3)."); 4–5 ("A second type of tipping point may also affect the AMOC. An important part of the sinking process in the northern Atlantic (called "deep water formation") is deep vertical mixing (convection) when the water column becomes vertically unstable, due to denser water sitting above less dense water. … There are two main convection regions within the present-day AMOC: one in the northern Atlantic subpolar gyre region (including the Labrador and Irminger Seas) and one further north in the Nordic Seas. In many model experiments, the Labrador Sea convection has been prone to shut down (Weijer et al., 2019), slowing not just the AMOC but also the subpolar gyre, a huge counterclockwise rotating flow south of Greenland and Iceland (Figure 4). Once convection (which normally extracts heat from the water column by mixing warmer water up to the surface, where heat is lost to the atmosphere) has been capped in this way, less heat gets lost through the sea surface, and the whole water column gets less dense. This slows the AMOC, which after all is driven by the cold, high-density waters pushing south from the high latitudes. Thus, a convection shutdown can help trigger an AMOC shutdown. And because convection is a small-scale process, it is not captured well in most current models (Jackson et al., 2023), adding a layer of uncertainty about the future.").

[560] McCarthy G. D. & Caesar L. (2023) *Can we trust projections of AMOC weakening based on climate models that cannot reproduce the past?*, PHIL. TRANS. R. SOC. A. 381(2262): 1–14, 3 ("The longest record of such a continuous directly measured AMOC time series is from the RAPID-MOCHA-WBTS programme [**15**], which started in 2004, and other observational programs have begun since then. For the time period pre-2004, estimates of AMOC strength can be derived from (a) single point (snapshots) of direct, cross-basin AMOC observations from shipboard hydrography [**27**], (b) historical hydrographic data based on the link between changes in density of water masses and associated transports [**17**,**20**,**28**], (c) satellite and/or hydrographic data based on the empirical correlations between the AMOC and sea surface height variability [**18**,**19**], (d) ocean temperature or salinity observations based on the link between AMOC, and heat and freshwater transport [**14**,**29**,**30**], (e) paleo-proxy data that have been linked to AMOC through physical processes or in model simulations [**13**,**31**]. By design and data availability, the different types of AMOC estimates cover different time spans."). *See also* Liu Z. (2023) *Evolution of Atlantic Meridional Overturning Circulation since the last glaciation: model simulations and relevance to present and future*, PHIL. TRANS. R. SOC. A. 381(2262): 1–23, 1–2 ("Paleoclimate proxies suggest that the Atlantic Meridional Overturning Circulation (AMOC) and the associated water masses have experienced dramatical changes in the past with magnitudes much beyond those in the instrument period. Furthermore, these AMOC changes were accompanied by climate changes and abrupt events over the globe [**1**,**2**]. … The different behaviour of uranium decay-series nuclides of protactinium and thorium, expressed as $^{231}Pa/^{230}Th$, from sediments in the North Atlantic is considered a proxy of the rate of deep Atlantic circulation, because ^{231}Pa has a longer residence time than ^{230}Th (111 years versus 26 years) such that the sediment $^{231}Pa/^{230}Th$ decreases with increased export of Atlantic deep water [**6**]. … Finally, large variability is also found accompanying deep ocean changes in the proxy for surface air temperature in Greenland and Antarctica ice cores as indicated in the stable water isotope composition in precipitation $\delta^{18}O$, which represents annual temperature via the 'temperature effect' associated with Rayleigh distillation [**8**] (figure 1*a*,*b*)."); *and* Hansen J., *et al.* (2016) *Ice melt, sea level rise and superstorms: evidence from paleoclimate data, climate modeling, and modern observations that 2 °C global warming could be dangerous*, ATMOS. CHEM. PHYS. 16(6): 3761–3812.

[561] van Westen R. M., Kliphuis M., & Dijkstra H. A. (2024) *Physics-based early warning signal shows that AMOC is on tipping course*, SCI. ADV. 10(6): 1–11, 1–2 ("This result differs substantially from earlier model simulations with GCMs that have used extremely large freshwater forcing [e.g., 1 Sv per year over 50°N to 70°N (20)] or large initial salinity perturbations (21). The AMOC collapse in these simulations is a direct response to the very strong forcing, whereas in our model simulations, which are more akin to the simulations in Earth System Models of Intermediate

Complexity (17, 18), the collapse is primarily a response due to internal feedbacks. … Also, on the basis of the change in the AMOC per forcing change (here about 8-Sv AMOC change due to a forcing change of 0.03 Sv), it is clear that we found an AMOC tipping event (6) in the CESM simulation, which is the first one found in a complex GCM.”). *See also* Lohmann J. & Ditlevsen P. D. (2021) *Risk of tipping the overturning circulation due to increasing rates of ice melt*, PROC. NAT'L. ACAD. SCI. 118(9): 1–6.

[562] Li Q., England M. H., Hogg A. M., Rintoul S. R., & Morrison A. K. (2023) *Abyssal ocean overturning slowdown and warming driven by Antarctic meltwater*, NATURE 615(7954): 841–847, 845, 847 (“The strength of the AABW overturning cell and the AMOC is projected to decrease by 42% (10.0 Sv) and 19% (2.8 Sv) by 2050, respectively. Meltwater forcing drives virtually all of the reduction in overturning in the AABW cell (Fig. 3d,e), with seawater ageing along the pathway of AABW outflow (Extended Data Fig. 11). The projected decline of AMOC results in reduced northward ocean heat transport, leading to a cooling trend in the abyssal Atlantic Ocean (Fig. 2). In contrast, the projected decline of AABW drives a warming trend across the abyssal Southern Ocean (Fig. 2), reminiscent in structure to recently observed bottom water trend.”; “We have shown that projected increases in Antarctic ice melt are set to drive a substantial slowdown of the lower cell of the global overturning circulation over the coming decades, resulting in large and widespread warming of deep waters and reduced ventilation of the abyssal ocean. In particular, a net slowdown of the abyssal ocean overturning circulation of just over 40% is projected to occur by 2050. These changes in the lower cell would profoundly alter the ocean overturning of heat, fresh water, oxygen, carbon and nutrients, with impacts felt throughout the global ocean for centuries to come.”). *See also* Golledge N. R., Keller E. D., Gomez N., Naughten K. A., Bernales J., Trusel L. D., & Edwards T. L. (2019) *Global environmental consequences of twenty-first-century ice-sheet melt*, NATURE 566(7742): 65–72.

[563] Lohmann J. & Ditlevsen P. D. (2021) *Risk of tipping the overturning circulation due to increasing rates of ice melt*, PROC. NAT'L. ACAD. SCI. 118(9): 1–6, 1, 4 (“Here we show that rate-induced transitions are indeed a concern for the climate system, by demonstrating explicitly the existence of a rate-induced collapse of the AMOC in a three-dimensional model of the global thermohaline circulation with time-dependent freshwater forcing…. From Fig. 3A it is clear that there is no well-defined critical rate separating tipping from tracking realizations. For T > 150 y all realizations track. For 50 y < T < 150 y there is a mixed pattern with some realizations tipping, some tracking, and others visiting the edge state. While for T < 50 y most realizations tip, this is still not guaranteed, since we find a realization for T = 10 y that evolves toward the edge state. Nevertheless, the probability of tipping increases with the rate, comparable to systems with added noise (28).”). *See also* Ritchie P. D. L., Alkhayuon H., Cox P. M., & Wieczorek S. (2023) *Rate-induced tipping in natural and human systems*, EARTH SYST. DYN. 14(3): 669–683, 676 (“For slow rates of increase in freshwater hosing, the system continually adapts and remains within the changing basin of attraction of the base state so that solutions converge to the final base state (the green trajectory). On the other hand, for sufficiently fast rates of increase in freshwater hosing, the system is unable to adapt and falls outside the changing basin of attraction of the base state, causing solutions to converge to the final alterna- tive state (the red trajectory).”).

[564] Douville H., *et al*. (2021) *Chapter 8: Water Cycle Changes*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 1055–1210, 1148 (“These patterns of past hydroclimatic change are relevant for future projections because it is *very likely* that AMOC will weaken by 2100 in response to increased greenhouse gas emissions (Weaver et al., 2012; Drijfhout et al., 2015; Bakker et al., 2016; Reintges et al., 2017) (See also Section 9.2.3.1). Furthermore, there is *medium confidence* that the decline in AMOC will not involve an abrupt collapse before 2100 (Section 9.2.3.1).”). *See also* Fox-Kemper B., *et al.* (2021) *Chapter 9: Ocean, Cryosphere and Sea Level Change*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 1239 (“Projected AMOC decline by 2100 ranges from 24 [4 to 46] % in SSP1-2.6 to 39 [17–55] % in SSP5-8.5 (medium confidence) (Section 4.3.2.3). Note that these ranges are based on ensemble means of individual models, largely smoothing out internal variability. If single realizations are considered, the ranges become wider, especially by lowering the low end of the range (Section 4.3.2.3). In summary, it is very likely that AMOC will decline in the 21st century, but there is low confidence in the model's projected timing and magnitude.”); Arias P. A., *et al.* (2021) *Technical Summary*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.),

73 ("While there is *medium confidence* that the projected decline in the Atlantic Meridional Overturning Circulation (AMOC) (TS.2.4) will not involve an abrupt collapse before 2100, such a collapse might be triggered by an unexpected meltwater influx from the Greenland Ice Sheet. If an AMOC collapse were to occur, it would *very likely* cause abrupt shifts in the weather patterns and water cycle, such as a southward shift in the tropical rain belt, and could result in weakening of the African and Asian monsoons and strengthening of Southern Hemisphere monsoons."); Fox-Kemper B., *et al.* (2021) *Chapter 9: Ocean, Cryosphere and Sea Level Change*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 1211–1261, 1239 ("Both the AR5 (Collins et al., 2013) and the SROCC (Collins et al., 2019) assessed that an abrupt collapse of the AMOC before 2100 was *very unlikely*, but the SROCC added that by 2300 an AMOC collapse was *as likely as not* for high-emission scenarios. The SROCC also assessed that model-bias may considerably affect the sensitivity of the modelled AMOC to freshwater forcing. Tuning towards stability and model biases (Valdes, 2011; Liu et al., 2017; Mecking et al., 2017; Weijer et al., 2019) provides CMIP models a tendency toward unrealistic stability (*medium confidence*). By correcting for existing salinity biases, Liu et al. (2017) demonstrated that AMOC behaviour may change dramatically on centennial to millennial timescales and that the probability of a collapsed state increases. None of the CMIP6 models features an abrupt AMOC collapse in the 21st century, but they neglect meltwater release from the Greenland ice sheet and a recent process study reveals that a collapse of the AMOC can be induced even by small-amplitude changes in freshwater forcing (Lohmann and Ditlevsen, 2021). As a result, we change the assessment of an abrupt collapse before 2100 to *medium confidence* that it will not occur."); *and* Intergovernmental Panel on Climate Change (2023) AR6 SYNTHESIS REPORT: CLIMATE CHANGE 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 1–85, 43 ("The Atlantic Meridional Overturning Circulation is very likely to weaken over the 21st century for all considered scenarios (*high confidence*), however an abrupt collapse is not expected before 2100 (*medium confidence*). If such a low probability event were to occur, it would very likely cause abrupt shifts in regional weather patterns and water cycle, such as a southward shift in the tropical rain belt, and large impacts on ecosystems and human activities.").

[565] Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, REV. GEOPHYS. 61: 1–81, 7 ("However, current coupled climate models exhibit biases in surface ocean climatology that favor greater AMOC stability (W. Liu et al., 2014). A modeling analysis correcting for these biases and assuming a CO_2 doubling approximately between the RCP4.5 and RCP6.0 scenarios produced an AMOC collapse 300 years after the CO_2 perturbation (W. Liu et al., 2017), emphasizing a need to improve model physics to allow for more realistic AMOC predictions. An analysis of Earth system models uncovered one instance in which the AMOC declines in strength and then collapses during the 21st century (Drijfhout et al., 2015)."); *citing* Liu W., Liu Z., & Brady E. C. (2014) *Why is the AMOC Monostable in Coupled General Circulation Models?*, J. CLIM. 27(6): 2427–2443, 2427 ("It is found that the monostable AMOC in the control simulation is altered to a bistable AMOC in the flux-adjustment experiment because a reduction of the surface salinity biases in the tropical and northern North Atlantic leads to a reduction of the bias of freshwater transport in the Atlantic. In particular, the tropical bias associated with the double ITCZ reduces salinity in the upper South Atlantic Ocean and, in turn, the AMOC freshwater export, which tends to overstabilize the AMOC and therefore biases the AMOC from bistable toward monostable state."). *See also* Ditlevsen P. & Ditlevsen S. (2023) *Warning of a forthcoming collapse of the Atlantic meridional overturning circulation*, NAT. COMMUN. 14(4254): 1–12, 1 ("A forthcoming collapse of the Atlantic meridional overturning circulation (AMOC) is a major concern as it is one of the most important tipping elements in Earth's climate system[1,2,3]. In recent years, model studies and paleoclimatic reconstructions indicate that the strongest abrupt climate fluctuations, the Dansgaard-Oeschger events4, are connected to the bimodal nature of the AMOC[5,6]. Numerous climate model studies show a hysteresis behavior, where changing a control parameter, typically the freshwater input into the Northern Atlantic, makes the AMOC bifurcate through a set of co-dimension one saddle-node bifurcations[7,8,9]. State-of-the-art Earth-system models can reproduce such a scenario, but the inter-model spread is large and the critical threshold is poorly constrained[10,11]. Based on the CMIP5 generation of models, the AR6 IPCC report quotes a collapse in the 21st century to be very unlikely (medium confidence)[12]. Among CMIP6 models, there is a larger spread in the AMOC response to warming scenarios, thus an increased uncertainty in the assessment of a future collapse[13]. There are, however, model biases

toward overestimated stability of the AMOC, both from tuning to the historic climate record[14], poor representation of the deep water formation[15], salinity and glacial runoff[16].").

[566] Rosser J. P., Winkelmann R., & Wunderling N. (2024) *Polar ice sheets are decisive contributors to uncertainty in climate tipping projections*, COMMUN. EARTH ENVIRON. 5(1): 1–11, 2 ("CMIP models are known to still be missing key elements of the climate dynamics, have common components (thus not representing a fully independent ensemble) and have large degrees of uncertainty, as shown for the CMIP5 ensemble[24]. State-of-the-art CMIP6 models do not include coupled dynamic ice sheets, which renders them unable to represent the tipping dynamics of these elements or their links and interactions with other elements[25,26] (although some modelling efforts have been performed on coupled ice sheet-climate models in ISMIP6[27]). This can cause significant issues in the behaviour of the ocean and the influence of varying ice sheet melt on the overturning ocean circulations[28]. CMIP6 models also do not include sea level rise and the impacts of this on the wider climate system, which has to be calculated separately[29], leading to a loss of any potential feedbacks or cascading impacts. The biosphere and the links between it and other parts of the climate system have also been shown to be critical for future tipping points and predictions of the climate[15,30], but many CMIP6 models do not feature key Earth System Components (such as a dynamically simulated biosphere) and those that do have important biases[31,32]."). *See also* Golledge N. R., Keller E. D., Gomez N., Naughten K. A., Bernales J., Trusel L. D., & Edwards T. L. (2019) *Global environmental consequences of twenty-first-century ice-sheet melt*, NATURE 566(7742): 65–72, 65 ("Explicit representation of ice sheet discharge was not included in Coupled Model Intercomparison Project Phase 5, so climate impacts arising from this melt are currently not captured in the simulations most commonly used to inform governmental policy."); 68–69 ("Since current climate models are thought to overestimate the stability of the AMOC, it is possible that future ice-sheet meltwater fluxes may play an even more important role than we predict here.").

[567] Ditlevsen P. & Ditlevsen S. (2023) *Warning of a forthcoming collapse of the Atlantic meridional overturning circulation*, NAT. COMMUN 14(4254): 1–12, 6–7 ("We have provided a robust statistical analysis to quantify the uncertainty in observed EWSs for a forthcoming critical transition. The confidence depends on how rapidly the system is approaching the tipping point. With this, the significance of the observed EWSs for the AMOC has been established. This is a stronger result than just observing a significant trend in the EWS by, say, Kendall's τ test[27,33]. Here we calculate when the EWS are significantly above the natural variations. Furthermore, we have provided a method to not only determine whether a critical transition will happen but also an estimate of when it will happen. We predict with high confidence the tipping to happen as soon as mid-century (2025–2095 is a 95% confidence range). These results are under the assumption that the model is approximately correct, and we, of course, cannot rule out that other mechanisms are at play, and thus, the uncertainty is larger. However, we have reduced the analysis to have as few and sound assumptions as possible, and given the importance of the AMOC for the climate system, we ought not to ignore such clear indicators of an imminent collapse."), *discussed in* Rahmstorf S. (24 July 2023) *What is happening in the Atlantic Ocean to the AMOC?*, REALCLIMATE ("**10. There are possible Early Warning Signals (EWS).** New methods from nonlinear dynamics search for those warning signals when approaching tipping points in observational data, from cosmology to quantum systems. They use the critical slowing down, increasing variance or increasing autocorrelation in the variability of the system. There is the paper by my PIK colleague Niklas Boers (2021), which used 8 different data series (Figure 6) and concluded there is "strong evidence that the AMOC is indeed approaching a critical, bifurcation-induced transition." Another study, this time using 312 paleoclimatic proxy data series going back a millennium, is Michel et al. 2022. They argue to have found a "robust estimate, as it is based on sufficiently long observations, that the Atlantic Multidecadal Variability may now be approaching a tipping point after which the Atlantic current system might undergo a critical transition. And today (update!) a third comparable study by Danish colleagues has been published, Ditlevsen & Ditlevsen 2023, which expects the tipping point already around 2050, with a 95% uncertainty range for the years 2025-2095. Individual studies always have weaknesses and limitations, but when several studies with different data and methods point to a tipping point that is already quite close, I think this risk should be taken very seriously. Conclusion: Timing of the critical AMOC transition is still highly uncertain, but increasingly the evidence points to the risk being far greater than 10 % during this century – even rather worrying for the next few decades."). *See also* Smolders E. J. V., van Westen R. M. & Dijkstra H. A. (2024) *Probability Estimates of a 21st Century AMOC* Collapse, ARXIV (*preprint*): 1–19, 8 ("Our analysis provides a first probability estimate from reanalysis data which gives a mean tipping time estimation of 2050 with a 10 – 90% CI of 2037 – 2064."); *compare with* Lohmann J., Dijkstra H. A., Jochum M., Lucarini V., & Ditlevsen P. D. (2024) *Multistability and intermediate*

tipping of the Atlantic Ocean circulation, SCI. ADV. 10(12): 1–14, 2, 7–8 ("Unlike a full AMOC collapse, ITPs [Intermediate Tipping Points] comprise only small changes in mean AMOC strength, but they can often be associated with specific changes in the spatiotemporal variability of the ocean circulation. Occurring well before the eventual collapse, they complicate the task of predicting a collapse from observational time series."; "EWS [Early Warning Signals] might be observable before each ITP, since each corresponds to a loss of stability of an attractor. But because of the a priori unknown number of ITPs before the AMOC collapse, it may not be possible to distinguish EWS before an arbitrary ITP from EWS before the AMOC collapse.").

[568] Rosser J. P., Winkelmann R., & Wunderling N. (2024) *Polar ice sheets are decisive contributors to uncertainty in climate tipping projections*, COMMUN. EARTH ENVIRON. 5(1): 1–11, 5–6 ("As a specific case study, Fig.4 shows the impact of removing the GIS from the system of interacting climate components. We initially focus on the GIS as it is consistently one of the most important components in both the Sobol variance analysis (see Figs. 1 and 2) and the leave one out analysis (see Fig. 4), giving one of the biggest decreases in mean number of elements tipped when removed from the 1.5 °C scenario. At 1.5 °C, the impact of totally removing the GIS is a reduction of 46% in the mean number of elements tipped and components transitioned in the system, but it also has significant impacts on the qualitative behaviour of the system. As the GIS has a low tipping point (between 0.8 and 3.0 °C) and strong links to other tipping elements (AMOC, WAIS), it is a key initiator of cascades at low global warming levels. So, when it is removed, the amount of tipping events and cascading effects that we record in the other components is greatly reduced. Although these are the only elements with direct links to the GIS, there are cascading impacts through these links onto the entire system, so the outcome of removing the GIS is a significant reduction in tipping or transitioning for every investigated component.")

[569] Orihuela-Pinto B., England M. H., & Taschetto A. S. (2022) *Interbasin and interhemispheric impacts of a collapsed Atlantic Overturning Circulation*, NAT. CLIM. CHANG. 12(6): 558–565, 558 ("We find that an AMOC collapse drives a complex rearrangement of the global atmospheric circulation that affects all latitudes, from the tropics to the polar circulation of both hemispheres. We find that changes in the tropical Pacific involve a robust intensification of the Walker circulation, a weakening of the subtropical highs in the Southern Hemisphere and an intensification of the Amundsen Sea Low over west Antarctica."). *See also* Intergovernmental Panel on Climate Change (2023) AR6 SYNTHESIS REPORT: CLIMATE CHANGE 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 43 ("The Atlantic Meridional Overturning Circulation is very likely to weaken over the 21st century for all considered scenarios (*high confidence*), however an abrupt collapse is not expected before 2100 (*medium confidence*). If such a low probability event were to occur, it would very likely cause abrupt shifts in regional weather patterns and water cycle, such as a southward shift in the tropical rain belt, and large impacts on ecosystems and human activities."); *and* Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, REV. GEOPHYS. 61: 1–81, 5, 32–33 ("A slowdown or shutdown of the AMOC system would significantly affect regional and global climate patterns (L. C. Jackson et al., 2015; W. Liu et al., 2020). Paleoclimate evidence and numerical simulations have identified AMOC transitions and/or latitudi-nal shift of deep-water formation sites as potential drivers of multiple large, rapid shifts in past climate, including fast or abrupt changes occurring on timescales as short as a few decades (Alley et al., 2001; Bozbiyik et al., 2011; Brovkin et al., 2021; Clark et al., 2001; Ganopolski & Rahmstorf, 2001; Rahmstorf, 2002). The impacts of past AMOC shifts affected climate globally, significantly altering tropical rainfall patterns and causing heat redis-tribution between the northern and southern hemispheres (S. Li & Liu, 2022; Masson-Delmotte et al., 2013). Changes to the overturning circulation could also affect the ocean's strength as a heat and carbon sink (X. Chen & Tung, 2018; Fontela et al., 2016; Nielsen et al., 2019; Romanou et al., 2017) and heat redistribution (S. Li & Liu, 2022; W. Liu & Fedorov, 2019; X. Ma et al., 2020). … In Heinrich events, for example, large discharges of fresh ice from the Laurentide ice sheet into the North Atlantic are hypothesized to have been associated with slowing of the AMOC and cooling of the entire north-ern hemisphere, resulting in a shift of tropical precipitation maxima southward to dry and weaken the West African and South Asian summer monsoons while enhancing South American monsoon precipitation (Chiang & Bitz, 2005; Deplazes et al., 2013; Schneider et al., 2014; X. Wang et al., 2004). In these sorts of scenarios, monsoons may be responding predictably and even linearly to the abrupt forcing of extratropical climate; synchronous changes in insolation may "pace" or "trigger" these changes

(Cheng et al., 2016), but the nonlinear response may originate in midlatitude ocean-atmosphere dynamics. Such scenarios bear important lessons for the possible response of monsoons to abrupt changes in the Greenland or Antarctic ice sheets or the Atlantic Meridional Overturning Circulation.").

[570] Milkoreit M. (ed.) (2023) *Section 3: Governance of Earth system tipping points*, *in* *GLOBAL TIPPING POINTS REPORT 2023*, Lenton T. M., et al. (eds.), 33 (Table 3.3.1 shows "Impacts of ESTPs [Earth system tipping points]." For AMOC, these are: "Regional sea level changes (fall in convection region & North European Shelf seas, rise further south). Shift in jet stream and storm tracks affecting weather patterns in Europe, potential increase in extreme weather events, e.g. cold winters in Europe, south-ward hurricanes shift. Partial & temporary counteraction of global warming. Southward shift in ITCZ leading to drying in the Sahel and Southern Asia; Some models project drying in parts of the Amazon. Summer monsoon weakening and shifts in Africa and Asia. Up to 10°C cooling in North Atlantic and 3°C cooling in Northern Europe / Eastern Canada, warming amplification in Southern Hemisphere. Drastic shifts in many ecosystems on land and in the sea around the world, e.g. Amazon drying. Affects dust aerosols via monsoon disruption in those regions; ocean circulation changes can affect pollutant pathways. Shifted temperatures/precipitation &weather patterns/extremes no longer matching infrastructure tolerance ranges. Threat to food security because of impacts on marine life (reduction of plankton), changes in precipitation severely impacting agriculture (particularly wheat and maize) & food security (particularly in Europe). Warming amplification in Southern Hemisphere accelerating Antarctic Ice Sheet melt and coral bleaching, Amazon drying; monsoon (African and Asian) shifts accelerated. Conflicts over food and water, displacement from uninhabitable areas, anomie, financial crises, etc."). *See also* van Westen R. M., Kliphuis M., & Dijkstra H. A. (2024) *Physics-based early warning signal shows that AMOC is on tipping course*, SCI. ADV. 10(6): 1–11, 3 ("The Amazon rainforest also shows a drastic change in their precipitation patterns due to ITCZ shifts, and the dry season becomes the wet season and vice versa. These AMOC-induced precipitation changes could severely disrupt the ecosystem of the Amazon rainforest (7, 24, 25) and potentially lead to cascading tipping (26–28)….The European climate is greatly affected (Fig. 3A) under the AMOC collapse. Note that the corresponding changes occur within a relatively short period (model years 1750 to 1850) and under a very small change in surface freshwater forcing. The yearly averaged atmospheric surface temperature trend exceeds 1°C per decade over a broad region in northwestern Europe, and for several European cities, temperatures are found to drop by 5° to 15°C (Fig. 3C). The trends are even more notable when considering particular months (Fig. 3B). As an example, February temperatures for Bergen (Norway) will drop by about 3.5°C per decade (Fig. 3D)."). *See also* Ben-Yami M., Good P., Jackson L. C., Crucifix M., Hu A., Saenko O., Swingedouw D., & Boers N. (2024) *Impacts of AMOC Collapse on Monsoon Rainfall: A Multi-Model Comparison*, EARTH'S FUTURE 12(9): 1-17, 1, 2, 12 ("Models consistently suggest substantial disruptions for WAM [West African Monsoon], ISM [Indian Summer Monsoon], and EASM [East Asian Summer Monsoon] with shorter wet and longer dry seasons (-29.07%, -18.76%, and -3.78% ensemble mean annual rainfall change, respectively). Models also agree on changes for the SAM [South American Monsoon], suggesting rainfall increases overall, in contrast to previous studies. These are more pronounced in the southern Amazon (+43.79%), accompanied by decreasing dry-season length. Consistently across models, our results suggest a robust and major rearranging of all tropical monsoon systems in response to an AMOC collapse."; "Over half of the world's population live in climates dominated by tropical monsoons (Moon &Ha,2020; Wang etal.,2021). Most of these are in developing countries, where land use is dominated by agriculture, so depends heavily on the rain the monsoons bring. These regions are thus vulnerable to any changes in the characteristics of the monsoon rains, whether they are changes in the timing or the amount of rainfall (WRCP, 2023)."; "A key property of the impacts discussed in this work is that they persist for at least 100 years, and so are irreversible over a human lifetime… The impacts presented in this work could thus represent long-term changes that would persist even after a return to pre-industrial conditions.").

[571] Rahmstorf S. (2024) *Is the Atlantic Overturning Circulation Approaching a Tipping Point?*, OCEANOG.: 1–14, 11 ("Several studies show that if the AMOC weakens, sea levels on the American northeast coastline will rise more sharply (e.g., Levermann et al., 2005; Yin et al., 2010). The Coriolis force pushes moving water, in this case, in the Gulf Stream, to the right, away from the American coast. When the Gulf Stream weakens, less water is moved northward, causing water levels to rise inshore of the Gulf Stream, with models projecting a 15–20 cm rise by 2100 from this effect alone, in addition to other causes of rising seas. Coastal erosion, the frequency of nuisance flooding, and extent of storm surge damage will substantially increase.").

[572] Douville H., *et al.* (2021) *Chapter 8: Water Cycle Changes*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 1148–1149 ("As with the paleoclimate events, AMOC collapse results in a southward shift in the ITCZ that is most pronounced in the tropical Atlantic. This could cause drying in the Sahel region (Defrance et al., 2017) as well as Mesoamerica and northern Amazonia (Parsons et al., 2014; Chen et al., 2018c). AMOC collapse also causes the Asian monsoon systems to weaken (Liu et al., 2017b) (Figure 8.27b) counteracting the strengthening expected in response to elevated greenhouse gases (see Section 8.4.2). Europe is projected to experience moderate drying in response to AMOC collapse (Jackson et al., 2015)"), *discussed in* Velasquez-Manoff M. & White J. (3 March 2021) *In the Atlantic Ocean, Subtle Shifts Hint at Dramatic Dangers*, The New York Times ("The consequences could include faster sea level rise along parts of the Eastern United States and parts of Europe, stronger hurricanes barreling into the Southeastern United States, and perhaps most ominously, reduced rainfall across the Sahel, a semi-arid swath of land running the width of Africa that is already a geopolitical tinderbox.").

[573] Aðalgeirsdóttir, G., *et al.* (October 2024) Open Letter by Climate Scientists to the Nordic Council of Ministers ("We, the undersigned, are scientists working in the field of climate research and feel it is urgent to draw the attention of the Nordic Council of Ministers to the serious risk of a major ocean circulation change in the Atlantic. A string of scientific studies in the past few years suggests that this risk has so far been greatly underestimated. Such an ocean circulation change would have devastating and irreversible impacts especially for Nordic countries, but also for other parts of the world."), *discussed in* Icelandic Met Office (19 October 2024) Continued greenhouse gas emissions could trigger a regional cooling around the North Atlantic.

[574] Aðalgeirsdóttir, G., *et al.* (October 2024) *Open Letter by Climate Scientists to the Nordic Council of Ministers* ("[W]e urge the Council of Nordic Ministers to (a) initiate an assessment of this significant risk to the Nordic countries and (b) take steps to minimize this risk as much as possible. This could involve leveraging the strong international standing of the Nordic countries to increase pressure for greater urgency and priority in the global effort to reduce emissions as quickly as possible, in order to stay close to the 1.5 °C target set by the Paris Agreement.").

[575] Rahmstorf S. (9 February 2024) *New study suggests the Atlantic overturning circulation AMOC "is on tipping course"*, RealClimate; *discussing* van Westen R. M., Kliphuis M., & Dijkstra H. A. (2024) *Physics-based early warning signal shows that AMOC is on tipping course*, Sci. Adv. 10(6): 1–11.

[576] Rantanen M., Karpechko A. Y., Lipponen A., Nordling K., Hyvärinen O., Ruosteenoja K., Vihma T. & Laaksonen A. (2022) *The Arctic has warmed nearly four times faster than the globe since 1979*, Commun. Earth Environ. 3(168): 1–10, 3 ("During 1979–2021, major portions of the Arctic Ocean were warming at least four times as fast as the global average (Fig. 1c). The most extreme AA [Arctic amplification] values occur in the sea areas near Novaya Zemlya, which were locally warming up to seven times as fast as the global average. … In general, there are no regions within the Arctic Circle where AA[43] is smaller than two, apart from the northern North Atlantic."), *discussed in* Budryk Z. (11 August 2022) *Arctic warming up to four times as fast as global average: study*, The Hill. One recent study accounted for the influence of natural variability on Arctic amplification and found that approximately 75% of the increasing Arctic rate of warming is due to external (i.e., anthropogenic) forcing; *see* Zhou W., Leung L. R., & Lu J. (2024) *Steady threefold Arctic amplification of externally forced warming masked by natural variability*, Nat. Geosci.: 1–10, 6–7 ("For all possible periods longer than 30 years over 1967–2020, removing the effect of IPO on global mean temperature constrains the range of AA from 1.66–4.39 in observations (Fig. 5a) to 1.97–4.06 (Fig. 5b). Further removing the effect of AM on Arctic mean temperature constrains the range of the forced AA to 2.65–3.29 (Fig. 5c). For the periods of 1970–2004 and 1980–2014, the degree of AA is 2.09 and 3.98 in observations (Fig. 5a) but becomes 2.28 and 3.33 after removing the effect of IPO (Fig. 5b) and 2.85 and 2.94 after removing the effects of both IPO and AM (Fig. 5c). Thus, the degree of the externally forced AA, estimated by removing the effect of IPO and AM from observations, is consistently close to three throughout the historical period. … Furthermore, by excluding the effects of IPO and AM from the observed temperature trends, we reveal that the externally forced AA remains close to three throughout the historical period.").

[577] This includes an estimated ~41 Mt CH_4 yearly from the abrupt thaw events. Abrupt thaw emissions calculated from subfractions of wetland abrupt thaw, upland hillslope abrupt thaw, and lowland abrupt thaw from lakes, as shown in Table 1. Ramage J., *et al.* (2024) *The Net GHG Balance and Budget of the Permafrost Region (2000–2020) From Ecosystem Flux Upscaling*, GLOB. BIOGEOCHEM. CYCLES 38(4): 1–18, 1 ("Here, we construct the first comprehensive bottom-up budgets of CO_2, CH_4, and N_2O across the terrestrial permafrost region using databases of more than 1000 in situ flux measurements and a land cover-based ecosystem flux upscaling approach for the period 2000–2020. Estimates indicate that the permafrost region emitted a mean annual flux of 12 (− 606, 661) Tg CO_2–C yr^{-1} , 38 (22, 53) Tg CH_4–C yr^{-1} , and 0.67 (0.07, 1.3) Tg N_2O–N yr^{-1} to the atmosphere throughout the period. Thus, the region was a net source of CH_4 and N_2O, while the CO_2 balance was near neutral within its large uncertainties."), *discussed in* Sidik S. (15 April 2024) *Northern Permafrost Region Emits More Greenhouse Gases Than It Captures*, EOS ("Their results suggest that the area has already shifted from a sink to a small source of carbon. The researchers compiled many past estimates of greenhouse gas flux in various sections of the northern permafrost region to reveal how the entire area is responding to climate change. They found that the study area was a net source of CH_4 and N_2O between 2000 and 2020. Wetlands were some of the largest methane emitters, and lakes contributed substantially as well. Dry tundra was the biggest driver of N_2O release, and permafrost bogs were a close second."). For permafrost becoming a CO_2 source, *see* International Cryosphere Climate Initiative (2024) STATE OF THE CRYOSPHERE 2024: LOST ICE, GLOBAL DAMAGE, 29 ("Arctic permafrost releases high levels of carbon dioxide and methane in the fall and early winter as summer thaw grows progressively deeper, overwhelming the Arctic's ability to naturally balance itself through carbon sequestration from plant growth . In other words: permafrost in northern circumpolar regions has become a source of atmospheric carbon, which will increase over time if temperatures continue to rise.[2]"), *discussing* See C. R., *et al.* (2024) *Decadal increases in carbon uptake offset by respiratory losses across northern permafrost ecosystems*, NAT. CLIM. CHANG. 14(8): 853–862.

[578] Permafrost Pathways, *Mitigation policy* (*last visited* 9 June 2023) ("Depending on how hot we let it get, carbon emissions from Arctic permafrost thaw are expected to be in the range of 30 to more than 150 billion tons of carbon (110 to more than 550 Gt CO_2) this century, with upper estimates on par with the cumulative emissions from the entire United States at its current rate. To put it another way, permafrost thaw emissions could use up between 25 and 40 percent of the remaining carbon budget that would be necessary to cap warming at the internationally agreed-upon 2 degrees Celsius global temperature threshold established in the Paris Agreement."); *data from* Schuur E. A. G., McGuire A. D., Schädel C., Grosse G., Harden J. W., Hayes D. J., Hugelius G., Koven C. D., Kuhry P., Lawrence D. M., Natali S. M., Olefeldt D., Romanovsky V. E., Schaefer K., Turetsky M. R., Treat C. C., & Vonk J. E. (2015) *Climate change and the permafrost carbon feedback*, NATURE 520(7546): 171–179. *See also* International Cryosphere Climate Initiative (2023) STATE OF THE CRYOSPHERE REPORT 2023 – TWO DEGREES IS TOO HIGH, 31 ("Permafrost emissions today and in the future are on the same scale as large industrial countries but can be minimized if the planet remains at lower temperatures. If we limit warming to 1.5°C, emissions through 2100 will be about as large as those of India today, 2.5Gt/ year, totaling around 150Gt CO_2 by 2100. Should we instead reach 2°C, permafrost emissions will about equal those of the almost the entire European Union** today on an annual basis, 3–4Gt/year, for about 200 Gt CO_2-eq by 2100. Even higher temperatures, exceeding 3–4°C by 2100, will however likely result in up to 400Gt CO_2-eq additional carbon release from permafrost, adding the equivalent of adding another United States or China (currently 5–10Gt/year) annually to the global carbon budget through 2100.").

[579] Annual U.S. CO_2 emissions from Figure 1 in U.S. EPA *Climate Change Indicators: U.S. Greenhouse Gas Emissions* (*last visited* 13 June 2023).

[580] Armstrong McKay D. I. & Loriani S. (eds.) (2023) *Section 1: Earth systems tipping points*, in GLOBAL TIPPING POINTS REPORT 2023, Lenton T. M., *et al.* (eds.), 26 ("Current-generation climate models suggest a net positive impact of the permafrost carbon-climate feedback on global climate with estimates of additional warming of 0.05-0.7°C by 2100 (Schaefer et al., 2014, Burke et al., 2018, Kleinen and Brovkin, 2018, Nitzbon et al., 2023) based on low- to high-emissions scenarios, respectively. Methane emissions from permafrost could temporarily contribute up to 50 per cent of the permafrost-induced radiative forcing due to its higher warming potential (Walter Anthony et al., 2016, Turetsky et al., 2020, Miner et al., 2022). Overall, however, Canadell et al., (2021) summarise that "thawing terrestrial permafrost will lead to carbon release (high confidence), but there is low confidence in the timing, magnitude and relative roles of CO_2 and CH4" of the permafrost carbon-climate feedback.").

[581] Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, REV. GEOPHYS. 61: 1–81, 20 ("Today permafrost covers ∼23 million km^{2}of the planet, with 13–18 × 10^6 km^2 in the Arctic, 1.06 × 10^6 km^2 in the Tibetan plateau and 16–21 × 10^6 km^2 in subsea and Antarctic regions (Chadburn et al., 2017; Gruber, 2012; Sayedi et al., 2020; D. Zou et al., 2017). Total organic carbon content of all permafrost soils in the Northern Hemisphere is assessed to range between 1,460 and 1,700 Gt C, nearly twice the amount of carbon currently in the atmosphere (Olefeldt et al., 2016; Schuur et al., 2018). On a worldwide scale, permafrost carbon represents about one-third of all global soil carbon within the upper 3m (Jobbágy & Jackson, 2000; Schuur et al., 2015)"). *See also* Miner K. R., Turetsky M. R., Malina E., Bartsch A., Tamminen J., McGuire A. D., Fix A., Sweeney C., Elder C. D., & Miller C. E. (2022) *Permafrost carbon emissions in a changing Arctic*, NAT. REV. EARTH ENVIRON. 3: 55–67, 55 ("Permafrost underlies ~25% of the Northern Hemisphere land surface and stores an estimated ~1,700Pg (1,700Gt) of carbon in frozen ground, the active layer and talik[1,2]. Rapid anthropogenic warming and resultant thaw threaten to mobilize permafrost carbon stores[3,4], potentially increasing atmospheric concentrations of carbon dioxide (CO_2) and methane (CH_4), and converting the Arctic from a carbon sink to a carbon source."); Schuur E. A. G., *et al*. (2015) *Climate Change and the Permafrost Carbon Feedback*, NATURE 520: 171–179, 171 ("The first studies that brought widespread attention to permafrost carbon estimated that almost 1,700 billion tons of organic carbon were stored in terrestrial soils in the northern permafrost zone. The recognition of this vast pool stored in Arctic and sub-Arctic regions was in part due to substantial carbon stored at depth (.1 m) in permafrost, below the traditional zone of soil carbon accounting."); *and* World Bank & International Cryosphere Climate Initiative (2013) ON THIN ICE: HOW CUTTING POLLUTION CAN SLOW WARMING AND SAVE LIVES, 44.

[582] The majority of permafrost soil carbon is stored in the near-surface region (top 3 meters). *See* Westerveld L., Kurvits T., Schoolmeester T., Mulelid O. B., Eckhoff T. S., Overduin P. P., Fritz M., Lantuit H., Alfthan B., Sinisalo A., Miesner F., & Viitanen L.-K. (2023) ARCTIC PERMAFROST ATLAS, GRID-Arendal, 21 ("Even though near surface permafrost soils represent only 15 per cent of the total global soil area, they contain almost one-third of the world's soil carbon. Permafrost soils contain almost twice as much carbon as is currently found in the atmosphere.").

[583] Schaefer K., Lantuit H., Romanovsky V. E., Schuur E. A. G., & Witt R. (2014) *The Impact of the Permafrost Carbon Feedback on Global Climate*, ENVIRON. RES. LETT. 9: 1–9, 2 ("If temperatures rise and permafrost thaws, the organic material will also thaw and begin to decay, releasing carbon dioxide (CO_2) and methane (CH_4) into the atmosphere and amplifying the warming due to anthropogenic greenhouse gas emissions … The PCF [permafrost carbon feedback] is irreversible on human time scales because in a warming climate, the burial mechanisms described above slow down or stop, so there is no way to convert CO_2 into organic matter and freeze it back into the permafrost."). *See also* Schaefer K., Zhang T., Bruhwiler L., & Barrett A. P. (2011) *Amount and timing of permafrost carbon release in response to climate warming*, TELLUS B 63(2): 165–180.

[584] Wilkerson J., Dobosky R., Sayres D. S., Healy C., Dumas E., Baker B., & Anderson J. G. (2019) *Permafrost nitrous oxide emissions observed on a landscape scale using the airborne eddy-covariance method*, ATMOS. CHEM. PHYS. 19(7): 4257–4268, 4257 ("The microbial by-product nitrous oxide (N_2O), a potent greenhouse gas and ozone depleting substance, has conventionally been assumed to have minimal emissions in permafrost regions. This assumption has been questioned by recent in situ studies which have demonstrated that some geologic features in permafrost may, in fact, have elevated emissions comparable to those of tropical soils. However, these recent studies, along with every known in situ study focused on permafrost N_2O fluxes, have used chambers to examine small areas (< 50 m^2). In late August 2013, we used the airborne eddy-covariance technique to make in situ N_2O flux measurements over the North Slope of Alaska from a low-flying aircraft spanning a much larger area: around 310 km^2. We observed large variability of N_2O fluxes with many areas exhibiting negligible emissions. Still, the daily mean averaged over our flight campaign was 3.8 (2.2–4.7) mg N_2O m^{-2} d^{-1} with the 90 % confidence interval shown in parentheses. If these measurements are representative of the whole month, then the permafrost areas we observed emitted a total of around 0.04–0.09 g m^{-2} for August, which is comparable to what is typically assumed to be the upper limit of yearly emissions for these regions."). *See also* Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, REV. GEOPHYS. 61(e2021RG000757): 1–81, 23 ("Emissions of nitrous oxide—another potent greenhouse gas—from

permafrost also may be non-negligible (Voigt et al., 2020; Wilkerson et al., 2019) and require further study. In general, improved projections of hydrological changes within the permafrost region (Andresen et al., 2020) and better quantification of the rates of permafrost organic carbon mineralization into CO_2 versus CH_4 (or other greenhouse gases such as N_2O), and the fate of permafrost C exported as dissolved organic matter in aquatic environments remain active areas of study with major climate implications (J. C. Bowen et al., 2020; Laurion et al., 2020; Zolkos & Tank, 2020)").

585 Permafrost Pathways, *Course of Action: Mitigation Policy* (*last visited* 13 June 2023) ("Depending on how hot we let it get, carbon emissions from Arctic permafrost thaw are expected to be in the range of 30 to more than 150 billion tons of carbon (110 to more than 550 Gt CO_2) this century, with upper estimates on par with the cumulative emissions from the entire United States at its current rate. To put it another way, permafrost thaw emissions could use up between 25 and 40 percent of the remaining carbon budget that would be necessary to cap warming at the internationally agreed-upon 2 degrees Celsius global temperature threshold established in the Paris Agreement…. Despite the enormity of this problem, gaps in permafrost carbon monitoring and modeling are resulting in permafrost being left out of global climate policies, rendering our emissions targets fundamentally inaccurate. World leaders are in a race against time to reduce emissions and prevent Earth's temperature from reaching dangerous levels. The problem is, without including current and projected emissions from permafrost, this race will be impossible to finish…. 82% [o]f IPCC models do not include carbon emissions from permafrost thaw."). Annual U.S. CO_2 emissions from Figure 1 in United States Environmental Protection Agency, *Climate Change Indicators: U.S. Greenhouse Gas Emissions* (*last visited* 13 June 2023). Climate models may also underestimate how readily permafrost thaws in response to temperature changes; *see* Torn M. S., Abramoff R. Z., Vaughn L. J. S., Chafe O. E., Curtis J. B., & Zhu B. (2025) *Large emissions of CO_2 and CH_4 due to active-layer warming in Arctic tundra*, Nat. Commun. 16(1): 1–11, 5 ("Although ESMs are likely over-simplified, we followed current ESM practice in applying the same Q_{10} pan-Arctic and over the century. The difference in Q_{10} between our experimentally determined value and that imposed a priori implies an additional 2.0–10.2 Pg CO2 y^{-1} on average in the period 2080–2100 (with much higher values in 2100), depending on the SSP.").

586 International Cryosphere Climate Initiative (2024) STATE OF THE CRYOSPHERE 2024: LOST ICE, GLOBAL DAMAGE, 30 (Figure 4.1 "Permafrost Emissions at 1.1°C" contains the caption "Committed annual permafrost emissions to 2100 will be about the scale of Japan's annual emissions today, about 0.5Gt/year, even with no further rise in temperature. DATA SOURCES: IPCC SR15, GASSER ET AL. (2018), TURETSKY ET AL. (2019)").

587 Smith S. L., O'Neill H. B., Isaksen K., Noetzli J., & Romanovsky V. E. (2022) *The changing thermal state of permafrost*, NAT. REV. EARTH ENVIRON. 3: 10–23, 10 ("In warmer permafrost (temperatures close to 0 °C), rates of warming are typically less than 0.3 °C per decade, as observed in sub-Arctic regions. In colder permafrost (temperatures less than −2 °C), by contrast, warming of up to about 1 °C per decade is apparent, as in the high-latitude Arctic. Increased active-layer thicknesses have also been observed since the 1990s in some regions, including a change of 0.4 m in the Russian Arctic."). *See also* Gulev S. K., Thorne P. W., Ahn J., Dentener F. J., Domingues C. M., Gerland S., Gong D., Kaufman D. S., Nnamchi H. C., Quaas J., Rivera J. A., Sathyendranath S., Smith S. L., Trewin B., von Schuckmann K., & Vose R. S. (2021) *Chapter 2: Changing State of the Climate System*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 348 ("Recent (2018–2019) permafrost temperatures in the upper 20–30 m layer (at depths where seasonal variation is minimal) were the highest ever directly observed at most sites (Romanovsky et al., 2020), with temperatures in colder permafrost of northern North America being more than 1°C higher than they were in 1978. Increases in temperature of colder Arctic permafrost are larger (average 0.4°C–0.6°C per decade) than for warmer (temperature >–2° C) permafrost (average 0.17°C per decade) of sub-Arctic regions (Figures 2.25, 9.22).").

588 Note that PgC_{eq} for the methane feedback is converted to $GtCO_2eq$ by multiplying by 44/12. Canadell J. G., *et al.* (2021) *Chapter 5: Global Carbon and other Biogeochemical Cycles and Feedbacks*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 728, 737, 739 ("This new assessment, based on studies included in or published since SROCC (Schaefer et al., 2014; Koven et al., 2015c; Schneider von Deimling et al., 2015; Schuur et al., 2015; MacDougall and Knutti, 2016a; Gasser et al., 2018; Yokohata et al., 2020), estimates that

the permafrost CO_2 feedback per degree of global warming (Figure 5.29) is 18 (3.1–41, 5th–95th percentile range) PgC $°C^{-1}$. The assessment is based on a wide range of scenarios evaluated at 2100, and an assessed estimate of the permafrost CH_4-climate feedback at 2.8 (0.7–7.3 5th–95th percentile range) Pg C_{eq} $°C^{-1}$ (Figure 5.29). This feedback affects the remaining carbon budgets for climate stabilisation and is included in their assessment (Section 5.5.2). … Beyond 2100, models suggest that the magnitude of the permafrost carbon feedback strengthens considerably over the period 2100–2300 under a high-emissions scenario (Schneider von Deimling et al., 2015; McGuire et al., 2018). Schneider von Deimling et al., (2015) estimated that thawing permafrost could release 20–40 PgC of CO_2 in the period from 2100 to 2300 under a RCP2.6 scenario, and 115–172 PgC of CO_2 under a RCP8.5 scenario. The multi-model ensemble in (McGuire et al., 2018) project a much wider range of permafrost soil carbon losses of 81–642 PgC (mean 314 PgC) for an RCP8.5 scenario from 2100 to 2300, and of a gain of 14 PgC to a loss of 54 PgC (mean loss of 17 PgC) for an RCP4.5 scenario over the same period … Methane release from permafrost thaw (including abrupt thaw) under high-warming RCP8.5 scenario has been estimated at 836–2614 Tg CH_4 over the 21st century and 2800–7400 Tg CH_4 from 2100–2300 (Schneider von Deimling et al., 2015), and as 5300 Tg CH_4 over the 21st century and 16000 Tg CH_4 from 2100–2300 (Turetsky et al., 2020). For RCP4.5, these numbers are 538–2356 Tg CH_4 until 2100 and 2000-6100 Tg CH_4 from 2100–2300 (Schneider von Deimling et al., 2015), and 4100 Tg CH_4 until 2100 and 10000 Tg CH_4 from 2100–2300 (Turetsky et al., 2020) … Land biosphere models show high agreement that long-term warming will increase N_2O release from terrestrial ecosystems (XuRi et al., 2012; B.D. Stocker et al., 2013; Zaehle, 2013; Tian et al., 2019). A positive land N_2O climate feedback is consistent with paleoevidence based on reconstructed and modelled emissions during the last deglacial period (Schilt et al., 2014; H. Fischer et al., 2019; Joos et al., 2020). The response of terrestrial N_2O emissions to atmospheric CO_2 increase and associated warming is dependent on nitrogen availability (van Groenigen et al., 2011; Butterbach-Bahl et al., 2013; Tian et al., 2019). Model-based estimates do not account for the potentially strong emissions increases in boreal and arctic ecosystems associated with future warming and permafrost thaw (Elberling et al., 2010; Voigt et al., 2017). There is medium confidence that the land N_2O climate feedback is positive, but low confidence in the magnitude (0.02 ± 0.01 W m^{-2} $°C^{-1}$). … Other feedback contributions, such as the non-CO_2 biogeochemical feedback, can be converted into a carbon-equivalent feedback term (γ; Section 5.4.5.5, 7.6) by reverse application of the linear feedback approximation (Gregory et al., 2009). The contributions of non-CO_2 biogeochemical feedbacks combine to a linear feedback term of 30 ± 27 PgC_{eq} $°C^{-1}$ (1 standard deviation range, 111 ± 98 Gt CO_2-eq $°C^{-1}$), including a feedback term of –11 [–18 to –5] PgC_{eq} $°C^{-1}$ (5–95% range, –40 [–62 to –18] Gt CO_2-eq $°C^{-1}$) from natural CH_4 and N_2O sources. The biogeochemical feedback from permafrost thaw leads to a combined linear feedback term of -21 ± 12 PgC_{eq} $°C^{-1}$ (1 standard deviation range –77 ± 44 Gt CO_2-eq $°C^{-1}$).”).

[589] International Cryosphere Climate Initiative (2023) State of the Cryosphere Report 2023 – Two Degrees is Too High, 29 (“Even at 1.5°C, studies indicate significant permafrost thaw and related emissions due to the dynamics outlined above, but these will be less in scale since temperatures will “only” average 3–4°C higher than today in the Arctic. “Very low” emissions (SSP1-1.9 also result in temperatures declining to below 1.4°C by the end of this century, preventing most additional new thaw. Summer Arctic sea ice also is mostly restored by this “very low” emissions level, helping to stabilize or decrease summer Arctic temperatures and extreme heat. Annual permafrost emissions will still need to be offset by future generations, but should be 30–50% less, more on the scale of India in 2019 (150Gt by 2100).”).

[590] Turetsky M. R., Abbott B. W., Jones M. C., Walter Anthony K., Olefeldt D., Schuur E. A. G., Koven C., McGuire A. D., Grosse G., Kuhry P., Hugelius G., Lawrence D. M., Gibson C., & Sannel A. B. K. (2019) *Permafrost collapse is accelerating carbon release*, Nature 569(7754): 32–34, 33 (“Although abrupt permafrost thawing will occur in less than 20% of frozen land, it increases permafrost carbon release projections by about 50%. Gradual thawing affects the surface of frozen ground and slowly penetrates downwards. Sudden collapse releases more carbon per square metre because it disrupts stockpiles deep in frozen layers. Furthermore, because abrupt thawing releases more methane than gradual thawing does, the climate impacts of the two processes will be similar. So, together, the impacts of thawing permafrost on Earth’s climate could be twice that expected from current models.”).

[591] Armstrong McKay D. I. & Loriani S. (eds.) (2023) *Section 1: Earth systems tipping points*, in Global Tipping Points Report 2023, Lenton T. M., et al. (eds.), 24 (“Further, it is estimated that carbon emissions related to abrupt thaw processes could contribute an additional 40 per cent of emissions from newly formed features such as thaw

slumps and thermokarst lake and wetland formation, which may double the radiative forcing from circumpolar permafrost-soil carbon fluxes (Turetsky et al., 2020; Walther Anthony et al., 2018). However, these processes are dependent on local environmental conditions that are unevenly distributed across the permafrost region (Olefeldt et al., 2016). Thus, despite the rapid nonlinear response at local-to-regional scale, the permafrost thaw and carbon emissions from thermokarst processes are likely to aggregate to a near linear response globally (Nitzbon et al., 2023).”). *See also* Nitzbon J., Deimling T. S. von, Aliyeva M., Chadburn S. E., Grosse G., Laboor S., Lee H., Lohmann G., Steinert N., Stuenzi S., Werner M., Westermann S., & Langer M. (2024) *No respite from permafrost-thaw impacts in absence of a global tipping point*, NAT. CLIM. CHANGE 14(6): 573–585, 580–581 (“The best estimate based on CMIP6 model projections for twenty-first-century carbon release due to gradual permafrost thaw in response to an increase in GMST amounts to 18 (confidence interval 3–41) PgC °C⁻1 due to CO_2 emissions[17], and another 2.8 (0.7–7.3) PgC_{eq} $°C^{-1}$ due to CH_4 emissions[17] (Fig. 5, gradual thaw). Thermokarst-related carbon emissions are estimated to contribute another 40% to the simulated carbon release from gradual thaw[29] (Fig. 5, rapid thaw). Even under net zero or negative emissions scenarios, permafrost carbon release may continue to increase[109–111] as temporary temperature overshoots will expose permafrost regions to elevated temperatures for longer than in non-overshoot scenarios (Fig. 5, overshoots), and may also enhance the abundance and magnitude of rapid local-scale thaw processes and feedbacks.”); *and* International Cryosphere Climate Initiative (2023) STATE OF THE CRYOSPHERE REPORT 2023 – TWO DEGREES IS TOO HIGH, 34 (“The greatest global risk, however, arises from the additional carbon released, which will decrease the carbon budget available to countries to prevent temperatures from rising above 1.5°, 2°C or more.”).

592 Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, REV. GEOPHYS. 61: 1–81, 50 (“Gradual permafrost thaw (Section 2.4) could contribute significant additional carbon emissions over the near-term (92 Gt C by 2100 under RCP8.5) (Meredith et al., 2019). Abrupt permafrost thaw processes acting over faster timescales could emit up to ∼18 Gt C by 2100 including considerable methane (Turetsky et al., 2019, 2020). Over this century, emissions from abrupt thaw could contribute approximately 6,771 Mt CH_4 (Mt C) and 10.95 Gt CO_2 (Gt C) under the worst-case RCP8.5 scenario (Turetsky et al., 2020).”). *See also* Turetsky M. R., Abbott B. W., Jones M. C., Anthony K. W., Olefeldt D., Schuur E. A. G., Grosse G., Kuhry P., Hugelius G., Koven C., Lawrence D. M., Gibson C., Sannel A. B. K., & McGuire A. D. (2020) *Carbon release through abrupt permafrost thaw*, NAT. GEOSCI. 13(2): 138–143, 139 (“Gradual permafrost thaw (Section 2.4) could contribute significant additional carbon emissions over the near-term (92 Gt C by 2100 under RCP8.5) (Meredith et al., 2019). Abrupt permafrost thaw processes acting over faster timescales could emit up to ∼18 Gt C by 2100 including considerable methane (Turetsky et al., 2019, 2020). Over this century, emissions from abrupt thaw could contribute approximately 6,771 Mt CH_4 (Mt C) and 10.95 Gt CO_2 (Gt C) under the worst-case RCP8.5 scenario (Turetsky et al., 2020).”).

593 Turetsky M. R., Abbott B. W., Jones M. C., Anthony K. W., Olefeldt D., Schuur E. A. G., Grosse G., Kuhry P., Hugelius G., Koven C., Lawrence D. M., Gibson C., Sannel A. B. K., & McGuire A. D. (2020) *Carbon release through abrupt permafrost thaw*, NAT. GEOSCI. 13: 138–143, 138–139 (“The permafrost zone is expected to be a substantial carbon source to the atmosphere, yet large-scale models currently only simulate gradual changes in seasonally thawed soil. Abrupt thaw will probably occur in <20% of the permafrost zone but could affect half of permafrost carbon through collapsing ground, rapid erosion and landslides. Here, we synthesize the best available information and develop inventory models to simulate abrupt thaw impacts on permafrost carbon balance. Emissions across 2.5 million km^2 of abrupt thaw could provide a similar climate feedback as gradual thaw emissions from the entire 18 million km^2 permafrost region under the warming projection of Representative Concentration Pathway 8.5. While models forecast that gradual thaw may lead to net ecosystem carbon uptake under projections of Representative Concentration Pathway 4.5, abrupt thaw emissions are likely to offset this potential carbon sink. Active hillslope erosional features will occupy 3% of abrupt thaw terrain by 2300 but emit one-third of abrupt thaw carbon losses. Thaw lakes and wetlands are methane hot spots but their carbon release is partially offset by slowly regrowing vegetation. After considering abrupt thaw stabilization, lake drainage and soil carbon uptake by vegetation regrowth, we conclude that models considering only gradual permafrost thaw are substantially underestimating carbon emissions from thawing permafrost. … Our simulations suggest net cumulative abrupt thaw carbon emissions on the order of 80±19PgC by 2300 (Fig. 2a). For context, a recent modelling study found that gradual vertical thaw could result in permafrost carbon losses of 208PgC by 2300 under RCP8.5 (multimodel mean), although model projections ranged from a net carbon gain of 167PgC to a net loss of 641PgC (ref. 2). Thus, our results suggest that abrupt thaw carbon losses are equivalent to approximately

40% of the mean net emissions attributed to gradual thaw. Most of this carbon release stems from newly formed features that cover <5% of the permafrost region"). *See also* Schuur E. A. G., *et al.* (2022) *Permafrost and Climate Change: Carbon Cycle Feedbacks from the Warming Arctic*, ANNU. REV. ENVIRON. RESOUR. 47: 343–371, 351 ("Research at the global scale that links these effects across both lowlands and uplands showed that 20% of the northern permafrost region was considered susceptible to past and future abrupt thaw (47). Importantly, this area also stores 50% of the near-surface soil carbon showing the correlation between carbon and ice accumulation that heightens the risk of abrupt thaw to climate change. Since ESMs do not simulate abrupt thaw, dynamics of ecosystem change including carbon cycling have been represented by a different class of regional models that track soil carbon losses as well as carbon gains from plant growth through ecological succession following abrupt thaw. The most comprehensive of these succession models that included the response of abrupt thaw across uplands and lowlands found that an additional 40% more net ecosystem carbon (80 ± 19 Pg C) would be released by 2300 (48) as compared to the ensemble estimate of net ecosystem carbon release from the PCN-MIP (30), which as described previously, only tracked the effect of gradual top-down permafrost thaw as the climate warms. Most of this additional 40% carbon release is attributed to new abrupt thaw features that cover <5% of the permafrost region. Moreover, plant growth in the succession model offset approximately 20% of the permafrost carbon release, a much lower proportion as compared to the estimate from ESMs in the PCN-MIP. Furthermore, the abrupt thaw succession model could track CH_4, in contrast to the PCN-MIP, which did not, and showed that approximately 20% of the net carbon loss from abrupt thaw could be emitted as CH_4, which contributed 50% of the radiative forcing due to its higher global warming potential. These findings are consistent with other abrupt thaw models that considered subsets of the Arctic permafrost landscape such as lake expansion in lowlands (26, 27)."); *and* Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, REV. GEOPHYS. 61: 1–81, 21 ("The majority of permafrost thaw will occur via thickening of the active layer, often referred to as gradual perma-frost thaw because it affects centimeters of surface permafrost relatively slowly on a time scale of decades to centuries (McGuire et al., 2018; Schneider Von Deimling et al., 2015). Abrupt thaw processes—the collective term for rapid erosion, thermokarst (thaw that leads to subsidence, land slumping, and erosion), and similar phenomena—lead to more abrupt exposure and thaw of permafrost on time scales of days to years (Abbott & Jones, 2015)…Abrupt thaw represents an important ecosystem state change (M. G. Turner et al., 2020) and has the potential to impact <20% of the Arctic region (Olefeldt et al., 2016; Turetsky et al., 2020). Such processes carry implications not just for susceptibility to thaw but also for subsequent rates of carbon release. Carbon mobilized by thermokarst events particularly in Yedoma perma-frost soils (a type of Pleistocene aged permafrost) has demonstrated rapid rates of biodegradation, underlining the potential for significant carbon release from thermokarst features (Vonk et al., 2013).").

[594] International Cryosphere Climate Initiative (2023) STATE OF THE CRYOSPHERE REPORT 2023 – TWO DEGREES IS TOO HIGH, 29.

[595] Abbott B. W., *et al.* (2016) *Biomass offsets little or none of permafrost carbon release from soils, streams, and wildfire: an expert assessment*, ENVIRON. RES. LETT. 11(3): 1–13, 3 ("Precise empirical or model-based assessments of the critical factors driving carbon balance are unlikely in the near future, so to address this gap, we present estimates from 98 permafrost-region experts of the response of biomass, wildfire, and hydrologic carbon flux to climate change. Results suggest that contrary to model projections, total permafrost-region biomass could decrease due to water stress and disturbance, factors that are not adequately incorporated in current models. Assessments indicate that end-of-the-century organic carbon release from Arctic rivers and collapsing coastlines could increase by 75% while carbon loss via burning could increase four-fold. Experts identified water balance, shifts in vegetation community, and permafrost degradation as the key sources of uncertainty in predicting future system response. In combination with previous findings, results suggest the permafrost region will become a carbon source to the atmosphere by 2100 regardless of warming scenario but that 65%–85% of permafrost carbon release can still be avoided if human emissions are actively reduced.").

[596] Schuur E. A. G., *et al.* (2022) *Permafrost and Climate Change: Carbon Cycle Feedbacks from the Warming Arctic*, ANNU. REV. ENVIRON. RESOUR. 47: 343–371, 362 ("The recent appearance of "craters" with high concentrations of CH_4 in some parts of Siberia have raised new questions (133). This phenomenon is a surprise to the permafrost community and appears to be connected with potential CH_4 emissions. Each crater does not contain exceptional levels

of CH_4 but could represent new pathways from deep fossil methane that have previously been capped by permafrost. Sources of geologic methane have been observed where ice and permafrost are retreating (116), including subsea (25, 134), and could be new sources to the atmosphere at levels that are only poorly constrained by the projections synthesized in this review.") *See also* Froitzheim N., Majka J., & Zastrozhnov D. (2021) *Methane release from carbonate rock formations in the Siberian permafrost area during and after the 2020 heat wave*, PROC. NAT'L. ACAD. SCI. 118(32): 1–3, 1 ("In the Taymyr Peninsula and surroundings in North Siberia, the area of the worldwide largest positive surface temperature anomaly for 2020, atmospheric methane concentrations have increased considerably during and after the 2020 heat wave. Two elongated areas of increased atmospheric methane concentration that appeared during summer coincide with two stripes of Paleozoic carbonates exposed at the southern and northern borders of the Yenisey-Khatanga Basin, a hydrocarbon-bearing sedimentary basin between the Siberian Craton to the south and the Taymyr Fold Belt to the north. Over the carbonates, soils are thin to nonexistent and wetlands are scarce. The maxima are thus unlikely to be caused by microbial methane from soils or wetlands. We suggest that gas hydrates in fractures and pockets of the carbonate rocks in the permafrost zone became unstable due to warming from the surface. This process may add unknown quantities of methane to the atmosphere in the near future."), *discussed in* Carrington D. (2 August 2021) *Climate crisis: Siberian heatwave led to new methane emissions, study says*, THE GUARDIAN ("The Siberian heatwave of 2020 led to new methane emissions from the permafrost, according to research. Emissions of the potent greenhouse gas are currently small, the scientists said, but further research is urgently needed. Analysis of satellite data indicated that fossil methane gas leaked from rock formations known to be large hydrocarbon reservoirs after the heatwave, which peaked at 6C above normal temperatures. Previous observations of leaks have been from permafrost soil or under shallow seas."), *and* Mufson S. (3 August 2021) *Scientists expected thawing wetlands in Siberia's permafrost. What they found is 'much more dangerous'*, WASHINGTON POST.

[597] Natali S. M., Holdren J. P., Rogers B. M., Treharne R., Duffy P. B., Pomerance R., & MacDonald E. (2021) *Permafrost carbon feedbacks threaten global climate goals*, PROC. NAT'L. ACAD. SCI. 118(21): 1–3, 1 ("This global climate feedback is being intensified by the increasing frequency and severity of Arctic and boreal wildfires (8, 9) that emit large amounts of carbon both directly from combustion and indirectly by accelerating permafrost thaw. Fire-induced permafrost thaw and the subsequent decomposition of previously frozen organic matter may be a dominant source of Arctic carbon emissions during the coming decades (9)."). *See also* Walker X. J., Baltzer J. L., Cumming S. G., Day N. J., Ebert C., Goetz S., Johnstone J. F., Potter S., Rogers B. M., Schuur E. A. G., Turetsky M. R., & Mack M. C. (2019) *Increasing wildfires threaten historic carbon sink of boreal forest soils*, NATURE 572(7770): 520–523, 523 ("The frequency of boreal forest fires is projected to increase even more with expected climate warming and drying28 and, as a result, the total burned area is expected to increase to 130%–350% by mid-century29. These changes will increase the proportion of young forests vulnerable to burning and increase both the loss of legacy C per unit area burned and the expanse of forests transitioning from net C uptake over consecutive fire intervals to net C loss."); *and* Genet H., McGuire A. D., Barrett K., Breen A., Euskirchen E. S., Johnstone J. F., Kasischke E. S., Melvin A. M., Bennett A., Mack M. C., Rupp T. S., Schuur A. E. G., Turetsky M. R., & Yuan F. (2013) *Modeling the effects of fire severity and climate warming on active layer thickness and soil carbon storage of black spruce forests across the landscape in interior Alaska*, ENVIRON. RES. LETT. 8(4): 1–13, 2 ("In simulations that included the effects of both warming and fire at the regional scale, fire was primarily responsible for a reduction in organic layer thickness of 0.06 m on average by 2100 that led to an increase in active layer thickness of 1.1 m on average by 2100. The combination of warming and fire led to a simulated cumulative loss of 9.6 kgC m^{-2} on average by 2100. Our analysis suggests that ecosystem carbon storage in boreal forests in interior Alaska is particularly vulnerable, primarily due to the combustion of organic layer thickness in fire and the related increase in active layer thickness that exposes previously protected permafrost soil carbon to decomposition.").

[598] Natali S. M., Holdren J. P., Rogers B. M., Treharne R., Duffy P. B., Pomerance R., & MacDonald E. (2021) *Permafrost carbon feedbacks threaten global climate goals*, PROC. NAT'L. ACAD. SCI. 118(21): 1–3, 1 ("Fire-induced permafrost thaw and the subsequent decomposition of previously frozen organic matter may be a dominant source of Arctic carbon emissions during the coming decades (9)").

[599] Kim I.-W., Timmermann A., Kim J.-E., Rodgers K. B., Lee S.-S., Lee H., & Wieder W. R. (2024) *Abrupt increase in Arctic-Subarctic wildfires caused by future permafrost thaw*, NAT. COMMUN. 15(1): 1–11, 4–5 ("To further elucidate interactions between the land and atmosphere induced by abrupt soil drying that occurs after the thaw, we

analyze the time evolution of the surface energy budget in July over a representative location in western Siberia [65.5°N, 83.75°E]. After the abrupt soil drying, the Bowen ratio increases abruptly around 2050 (Fig. 3e). The latent heat flux abruptly decreases due to the loss of evapotranspiration (2040: 66.9 ± 14.1 W/m^2, 2060: 50.7 ± 10.3 W/m^2), accompanying a rapid increase in the sensible heat flux (2040: 16.8 ± 8.7 W/m^2 , 2060: 44.4 ± 10.4 W/m^2) (Fig. 3f, g). … Once the sensible heat flux increases abruptly following the abrupt soil drying, this can further accelerate an increase in surface air temperature, thus leading to a rapid decline in relative humidity (2040: 82.5 ± 5.1%, 2060: 68.6 ± 4.8%), despite a smaller change in the actual amount of water vapor (Figs. 3g, h, and S6b, c). … The abrupt soil drying and intensified atmospheric aridity can facilitate an abrupt increase in fires, related to biomass and peat burning over the permafrost regions. Abrupt increases in burned areas are pronounced over the historical permafrost regions (Fig. 4). The burned area after the rapid permafrost thaw is ~2.6 times greater than that observed during the pre-thaw period (Fig. S7). Over western Siberia [65.5°N, 83.75°E], the abrupt change in wildfire onset occurs following abrupt soil drying driven by rapid permafrost thaw (Figs. 1i, j, and 4c), and the timing of the abrupt wildfire onset is similar across the 50 ensemble members (Fig. 4c).").

[600] Westerveld L., Kurvits T., Schoolmeester T., Mulelid O. B., Eckhoff T. S., Overduin P. P., Fritz M., Lantuit H., Alfthan B., Sinisalo A., Miesner F., & Viitanen L.-K. (2023) ARCTIC PERMAFROST ATLAS, GRID-Arendal, 66 ("Greater summer rainfall can lead to increased permafrost thaw because of the high heat capacity of water. After very wet summers, thaw depths may take longer to return to "normal" values. Higher rainfalls have an even greater effect in disturbed areas, for example, where the ground has subsided due to permafrost thaw. Surface water ponding is not unusual in these sites and may lead to further thawing."). *See also* International Cryosphere Climate Initiative (2023) STATE OF THE CRYOSPHERE REPORT 2023 – TWO DEGREES IS TOO HIGH, 32 ("More incidents of extreme summer rainfall may increase the depth of permafrost thaw by more than 30%. Under a high emissions scenario, precipitation in the Arctic is projected to increase by 60% by 2100 and increasingly shift from snow to rain due to rising air temperatures.").

[601] Wu X., Macdonald R., & Wu T. (2023) *Coupled Changes in the Arctic Carbon Cycle Between the Land, Marine, and Social Domains*, EARTH'S FUTURE 11(12): 1–9, 3 ("The Arctic coastlines are particularly vulnerable to erosion because they consist of ice-rich permafrost (Grigoriev et al., 2004; Zimov et al., 2006). The Arctic coastlines exhibit the highest erosion rates in the world (Reimnitz et al., 1988). Arctic coastal erosion could significantly contribute to the Arctic carbon cycle as large quantities of organic carbon stored in permafrost are directly exported to the ocean (Fritz et al., 2017). Coastal erosion can breach thermokarst lakes, leading to the initial draining of the lakes followed by marine flooding. Additionally, coastal erosion and land loss poses a considerable threat to native, industrial, scientific, and even military communities (Ding et al., 2021). The Arctic coastal erosion is expected to increase drastically in the future due to the permafrost thaw, declining summer sea ice cover, longer and warmer thawing seasons, increasing seawater temperature, and rising sea level (Fritz et al., 2017; Gunther et al., 2015).").

[602] International Cryosphere Climate Initiative (2024) STATE OF THE CRYOSPHERE 2024: LOST ICE, GLOBAL DAMAGE, 29 ("Coastal permafrost erosion decreases the Arctic Ocean's capacity to absorb carbon dioxide, which could lead to a 14% reduction in uptake by 2100 under a worst-case scenario. Another way to frame it: coastal erosion could contribute to an annual increase in atmospheric carbon dioxide equivalent to 10% of all European car emissions in 2021. The findings have worrying implications for the Arctic Ocean's vital ability to act as a carbon sink."), *citing* Nielsen D. M., Chegini F., Maerz J., Brune S., Mathis M., Dobrynin M., Baehr J., Brovkin V., & Ilyina T. (2024) *Reduced Arctic Ocean CO_2 uptake due to coastal permafrost erosion*, NAT. CLIM. CHANG.: 1–8, 6 ("We estimated the reduction in the ocean CO_2 uptake due to erosion at 1–2 TgC yr^{-1} $°C^{-1}$ (GSAT) [global surface air temperature], which translates to a climate feedback of $\sim 10^{-3}$ W m^{-2} $°C^{-1}$ over 100 years. Our results allow coastal permafrost erosion to be considered in future climate projections and carbon budget assessments.").

[603] For a general discussion of impacts in Siberia, see Mellen R. & Saprunova N. (3 January 2024) *Siberia's ice is melting, revealing its past and endangering its future*, WASHINGTON POST.

[604] Hjort J., Streletskiy D., Doré G., Wu Q., Bjella K., & Luoto M. (2022) *Impacts of permafrost degradation on infrastructure*, NAT. REV. EARTH ENVIRON. 3: 24–38, 24 ("Permafrost change imposes various threats to infrastructure, namely through warming, active layer thickening and thaw-related hazards such as thermokarst and

mass wasting. These impacts, often linked to anthropogenic warming, are exacerbated through increased human activity. Observed infrastructure damage is substantial, with up to 80% of buildings in some Russian cities and ~30% of some road surfaces in the Qinghai–Tibet Plateau reporting damage. Under anthropogenic warming, infrastructure damage is projected to continue, with 30–50% of critical circumpolar infrastructure thought to be at high risk by 2050. Accordingly, permafrost degradation-related infrastructure costs could rise to tens of billions of US dollars by the second half of the century."). *See also* Hjort J., Karjalainen O., Aalto J., Westermann S., Romanovsky V. E., Nelson F. E., Etzelmüller B., & Luoto M. (2018) *Degrading permafrost puts Arctic infrastructure at risk by mid-century*, NAT. COMMUN. 9(5147): 1–9, 1 ("Here we identify at unprecedentedly high spatial resolution infrastructure hazard areas in the Northern Hemisphere's permafrost regions under projected climatic changes and quantify fundamental engineering structures at risk by 2050. We show that nearly four million people and 70% of current infrastructure in the permafrost domain are in areas with high potential for thaw of near-surface permafrost. Our results demonstrate that one-third of pan-Arctic infrastructure and 45% of the hydrocarbon extraction fields in the Russian Arctic are in regions where thaw-related ground instability can cause severe damage to the built environment. Alarmingly, these figures are not reduced substantially even if the climate change targets of the Paris Agreement are reached."). A higher estimate of hazard risk in the whole Northern Hemisphere is provided in Jin H., Peng X., Frauenfeld O. W., Huang Y., Guo L., Luo J., Yin G., Zhao G., & Mu C. (2024) *The infrastructure cost of permafrost degradation for the Northern Hemisphere*, GLOB. ENVIRON. CHANGE 84: 1–10, 5 ("Due to the rising MAGT and deepening of ALT, the hazard risk in permafrost regions of the Northern Hemisphere is increasing, however, with differences in the future scenarios and for the different types of permafrost—continuous, discontinuous, sporadic, and isolated permafrost. By 2085, the area proportions of medium–high hazards in Northern Hemisphere permafrost regions are 67 % for SSP1-2.6, 74 % for SSP2-4.5, 84 % for SSP3-7.0, and 86 % for SSP5-8.5 (Fig. 4).").

[605] Staalesen A. (29 June 2021) *The looming Arctic collapse: More than 40% of north Russian buildings are starting to crumble*, ARCTIC TODAY ("Aleksandr Kozlov, Russia's Minister of Natural Resources, told a minister's council in May that more than 40% of the northern region's buildings are starting to deform. Nearly 30% of oil and gas installations are inoperable. By 2050, Russian researchers estimate that the melting permafrost will inflict damages worth about $69 billion, about a quarter of the current Russian federal budget.").

[606] Jin H., Peng X., Frauenfeld O. W., Huang Y., Guo L., Luo J., Yin G., Zhao G., & Mu C. (2024) *The infrastructure cost of permafrost degradation for the Northern Hemisphere*, GLOB. ENVIRON. CHANGE 84: 1–10, 5 ("Our results show that by 2085, to ensure the infrastructure in Northern Hemisphere permafrost regions will remain fully operational, substantial additional costs will be incurred (Fig. 6). These costs for various infrastructure vary based on the different future scenarios. Under SSP5-8.5, the additional expenses are highest, which is consistent with our results regarding the magnitude of permafrost degradation. From the perspective of different infrastructure types, the additional costs required for roads are the highest, at $90–261 billion for SSP1-2.6, $102–289 billion for SSP2-4.5, $104–296 billion for SSP3-7.0, and $117–325 billion for SSP5-8.5. The projected additional costs for railways, pipelines, and airports are $44–122 billion, $43–119 billion, and $2–6 billion under the SSP5-8.5 scenario. The combined additional costs of various infrastructure will be $162–466 billion for SSP1-2.6, $179–508 billion for SSP2-4.5, $185–523 billion for SSP3-7.0, and $205–572 billion for SSP5-8.5 respectively.").

[607] Jin H., Peng X., Frauenfeld O. W., Huang Y., Guo L., Luo J., Yin G., Zhao G., & Mu C. (2024) *The infrastructure cost of permafrost degradation for the Northern Hemisphere*, GLOB. ENVIRON. CHANGE 84: 1–10, 5 ("Due to the rising MAGT [mean annual ground temperature] and deepening of ALT [active layer thickness], the hazard risk in permafrost regions of the Northern Hemisphere is increasing, however, with differences in the future scenarios and for the different types of permafrost—continuous, discontinuous, sporadic, and isolated permafrost. By 2085, the area proportions of medium–high hazards in Northern Hemisphere permafrost regions are 67 % for SSP1-2.6, 74 % for SSP2-4.5, 84 % for SSP3-7.0, and 86 % for SSP5-8.5 (Fig. 4).").

[608] Langer M., von Deimling T. S., Westermann S., Rolph R., Rutte R., Antonova S., Rachold V., Schultz M., Oehme A., & Grosse G. (2023) *Thawing permafrost poses environmental threat to thousands of sites with legacy industrial contamination*, NAT. COMMUN. 14(1721): 1–11, 1 ("Here we identify about 4500 industrial sites where potentially hazardous substances are actively handled or stored in the permafrost-dominated regions of the Arctic. Furthermore, we estimate that between 13,000 and 20,000 contaminated sites are related to these industrial sites. Ongoing climate

warming will increase the risk of contamination and mobilization of toxic substances since about 1100 industrial sites and 3500 to 5200 contaminated sites located in regions of stable permafrost will start to thaw before the end of this century."). *See also* Wu R., Trubl G., Taş N., & Jansson J. K. (2022) *Permafrost as a potential pathogen reservoir*, ONE EARTH 5(4): 351–360, 351 ("The Arctic is currently warming at unprecedented rates because of global climate change, resulting in thawing of large tracts of permafrost soil. A great challenge is understanding the implications of permafrost thaw on human health and the environment. Permafrost is a reservoir of mostly uncharacterized microorganisms and viruses, many of which could be viable.").

[609] Westerveld L., Kurvits T., Schoolmeester T., Mulelid O. B., Eckhoff T. S., Overduin P. P., Fritz M., Lantuit H., Alfthan B., Sinisalo A., Miesner F., & Viitanen L.-K. (2023) ARCTIC PERMAFROST ATLAS, GRID-Arendal, 119, 121 ("In the Arctic, permafrost has been an effective barrier in tailing deposits, preventing contaminants from seeping into the environment. However, as permafrost thaws and the ground ice within it melts, the hydraulic conductivity increases. This means that water, along with any dissolved elements, can move more easily and potentially infiltrate groundwater or local water bodies. As a results, relying on permafrost for tailings containment is no longer a viable option and other solutions are needed."; "If the underlying permafrost layer thaws, contaminants can seep into and pollute the surrounding environment, rivers, and groundwater. In addition, the waste itself can also cause local thawing in and around waste landfills. The actual amount of heating depends on the type of waste that is stored. Dumps of coal fragments, for example, can produce heat due to oxidation, while municipal solid waste sites produce heat because of decomposition. When the permafrost around landfills thaws, unfrozen areas in the permafrost known as talik zones are created under the waste, and leakages from the dumps into water and the ground can occur.").

[610] Wadhams P. (2017) A FAREWELL TO ICE: A REPORT FROM THE ARCTIC, Oxford University Press. *See also* Shakohva N., Semiletov I., & Chuvilin E. (2019) *Understanding the Permafrost-Hydrate System and Associated Methane Releases in the East Siberian Arctic Shelf*, GEOSCI. 9(251): 1–23; *and* Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, REV. GEOPHYS. 61: 1–81, 13 ("Early estimates of high rates of methane emissions from hydrate dissociation on the East Siberian Arctic Shelf (Shakhova et al., 2014) have been revised substantially downwards by numerous subsequent studies (Berchet et al., 2016; Thornton et al., 2016, 2020; Tohjima et al., 2020). Present-day marine methane release from Arctic hydrate dissociation is probably primarily of natural origin, resulting from the pressure decrease associated with isostatic uplift following the last glacial maximum, rather than a response to anthropogenic forcing (Wallmann et al., 2018). And in the Beaufort Sea, fossil methane possibly from hydrate emissions was observed in deeper waters but was removed, likely via oxidation, prior to atmospheric emission (Sparrow et al., 2018). In conclusion, while levels of warming exist beyond which large quantities of methane in hydrate deposits may eventually become destabilized, numerous physical, thermodynamic, chemical, and biological factors combine to substantially limit the rate at which this methane might escape to the atmosphere. For more moderate warming of ~2°C, methane hydrates might well exert a negligible overall impact on atmospheric temperatures. Methane hydrate dissociation would additionally take place on extremely long timescales of millennia, rather than over abrupt or fast timescales that would produce an acute warming spike…. With all of this in mind, in relation to other candidate tipping elements covered within this review, marine methane hydrates represent a relatively lower-impact climate feedback especially for warming in the Anthropocene (Table 3).").

[611] Weldeab S., Schneider R. R., Yu J., & Kylander-Clark A. (2022) *Evidence for massive methane hydrate destabilization during the penultimate interglacial warming*, PROC. NAT'L. ACAD. SCI. 119(35): 1–9, 7 ("While further studies are needed to determine the extent of methane hydrate destabilization during the weakened AMOC interval of the Eemian, the consequence of broad methane hydrate destabilization is increased atmospheric CH_4 and CO_2 concentrations. Taking age model uncertainties into consideration, during the peak in anomalously low carbon isotopes, the atmospheric CO_2 and CH_4 concentrations rose by 17 to 10 parts per million per volume and 20 parts per billion per volume, respectively (SI Appendix, Fig. S9) (49–51). Although the magnitude of this change varies between ice cores and analytical laboratories, the $\delta^{13}C$ values of atmospheric CO_2 declined by 0.3 to 0.4‰ coeval with the $\delta^{13}C$ anomaly recorded in the Gulf of Guinea sediment sequence (SI Appendix, Fig. S9) (50, 52), indicating that a source with a significantly negative $\delta^{13}C$ signature contributed to the increase of atmospheric CO_2. Methane release and methane oxidation due to massive methane hydrate destabilization is the likely source."). *See also* Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., &

Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, REV. GEOPHYS. 61: 1–81, 10–11 ("A significant time lag separates atmospheric warming due to climate change and the much longer timescales required for transport and diffusion of heat anomalies into the ocean and sediment. As sediment warming is required for methane hydrate instability, dissociation may not be initiated until centuries to millennia after the requisite warming spike (Archer, 2015; Archer et al., 2009; K. Kretschmer et al., 2015; Ruppel, 2011). For deep ocean sediments, tens of millennia might be required for the methane hydrate zone to begin appreciably warming, let alone for hydrate to begin dissociating (Archer et al., 2009; Ruppel, 2011). This factor does not preclude eventual significant release of carbon from methane hydrate, but does mean that this climate feedback occurs with a very substantial delay between commitment and realization.").

[612] Whiteman G., Hope C., & Wadhams P. (2013) *Vast costs of Arctic change*, NATURE 499(7459): 401–403, 401–403 ("We calculate that the costs of a melting Arctic will be huge, because the region is pivotal to the functioning of Earth systems such as oceans and the climate. The release of methane from thawing permafrost beneath the East Siberian Sea, off northern Russia, alone comes with an average global price tag of $60 trillion in the absence of mitigating action — a figure comparable to the size of the world economy in 2012 (about $70 trillion). The total cost of Arctic change will be much higher… The methane pulse will bring forward by 15–35 years the average date at which the global mean temperature rise exceeds 2°C above pre-industrial levels — to 2035 for the business-as-usual scenario and to 2040 for the low-emissions case (see 'Arctic methane'). This will lead to an extra $60 trillion (net present value) of mean climate-change impacts for the scenario with no mitigation, or 15% of the mean total predicted cost of climate-change impacts (about $400 trillion). In the low-emissions case, the mean net present value of global climate-change impacts is $82 trillion without the methane release; with the pulse, an extra $37 trillion, or 45% is added…. These costs remain the same irrespective of whether the methane emission is delayed by up to 20 years, kicking in at 2035 rather than 2015, or stretched out over two or three decades, rather than one. A pulse of 25 Gt of methane has half the impact of a 50 Gt pulse. The economic consequences will be distributed around the globe, but the modelling shows that about 80% of them will occur in the poorer economies of Africa, Asia and South America. … The full impacts of a warming Arctic, including, for example, ocean acidification and altered ocean and atmospheric circulation, will be much greater than our cost estimate for methane release alone. To find out the actual cost, better models are needed to incorporate feedbacks that are not included ….."). *See also* Wadhams P. (2017) A FAREWELL TO ICE: A REPORT FROM THE ARCTIC, Oxford University Press; *and* Shakohva N., Semiletov I., & Chuvilin E. (2019) *Understanding the Permafrost-Hydrate System and Associated Methane Releases in the East Siberian Arctic Shelf*, GEOSCI. 9(6): 251, 1–23.

[613] Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, REV. GEOPHYS. 61: 1–81, 13 ("Early estimates of high rates of methane emissions from hydrate dissociation on the East Siberian Arctic Shelf (Shakhova et al., 2014) have been revised substantially downwards by numerous subsequent studies (Berchet et al., 2016; Thornton et al., 2016, 2020; Tohjima et al., 2020). Present-day marine methane release from Arctic hydrate dissociation is probably primarily of natural origin, resulting from the pressure decrease associated with isostatic uplift following the last glacial maximum, rather than a response to anthropogenic forcing (Wallmann et al., 2018). And in the Beaufort Sea, fossil methane possibly from hydrate emissions was observed in deeper waters but was removed, likely via oxidation, prior to atmospheric emission (Sparrow et al., 2018. … In conclusion, while levels of warming exist beyond which large quantities of methane in hydrate deposits may eventually become destabilized, numerous physical, thermodynamic, chemical, and biological factors combine to substantially limit the rate at which this methane might escape to the atmosphere. For more moderate warming of ~2°C, methane hydrates might well exert a negligible overall impact on atmospheric temperatures. Methane hydrate dissociation would additionally take place on extremely long timescales of millennia, rather than over abrupt or fast timescales that would produce an acute warming spike…. With all of this in mind, in relation to other candidate tipping elements covered within this review, marine methane hydrates represent a relatively lower-impact climate feedback especially for warming in the Anthropocene (Table 3).").

[614] Ye W., Li Y., Wen J., Zhang J., Shakhova N., Liu J., Wu M., Semiletov I., & Zhan L. (2023) *Enhanced Transport of Dissolved Methane From the Chukchi Sea to the Central Arctic*, GLOB. BIOGEOCHEM. CYCLES 37(2): 1–21, 2 ("Here, based on our integrated data set (including 420 samples) and combined with previous studies (including 238

data points) (Fenwick et al., 2017; Kudo et al., 2018; Li et al., 2017; Lorenson et al., 2016), we find that CH_4 was significantly enhanced in the Chukchi Sea and distributed northward with the shelf-break jet, providing clear evidence of increased CH_4 transport from the Chukchi Sea shelf to the central Arctic in the 2010s compared with the 1990s.").

[615] Wadham J. L., Hawkings J. R., Tarasov L., Gregoire L. J., Spencer R. G. M., Gutjahr M., Ridgwell A., & Kohfeld K. E. (2019) *Ice sheets matter for the global carbon cycle*, NAT. COMMUN. 10(3567): 1–17, 8–9 ("There are substantial uncertainties regarding the magnitude of present day sub-ice sheet CH_4 hydrate reserves because of the difficulties of accessing sediments in subglacial sedimentary basins. Global subglacial methane hydrate stocks at the present day are likely to be dominated by those in Antarctic sedimentary basins (estimated at up to 300 Pg C as methane hydrate and free gas95). At the LGM, the global sub-ice sheet hydrate reserve could have been much larger (>500 Pg C, 20% of the present day marine hydrate stocks), with hydrate also present beneath former northern hemisphere ice sheets17,18,122 (see Fig. 4 for details and calculation methods). The vulnerability of Antarctic subglacial CH_4 hydrate reserves to destabilization is high because of their predicted location around the continent's periphery in sedimentary basins where ice thinning in a warming climate is probable."). *See also* Dessandier P.-A., Knies J., Plaza-Faverola A., Labrousse C., Renoult M., & Panieri G. (2021) *Ice-sheet melt drove methane emissions in the Arctic during the last two interglacials*, GEOLOGY 49(7): 799–803, 799 ("Here, we argue that based on foraminiferal isotope studies on drill holes from offshore Svalbard, methane leakage occurred upon the abrupt Eurasian ice-sheet wastage during terminations of the last (Weichselian) and penultimate (Saalian) glaciations. Progressive increase of methane emissions seems to be first recorded by depleted benthic foraminiferal $\delta^{13}C$. This is quickly followed by the precipitation of methane-derived authigenic carbonate as overgrowth inside and outside foraminiferal shells, characterized by heavy $\delta^{18}O$ and depleted $\delta^{13}C$ of both benthic and planktonic foraminifera. The similarities between the events observed over both terminations advocate a common driver for the episodic release of geological methane stocks. Our favored model is recurrent leakage of shallow gas reservoirs below the gas hydrate stability zone along the margin of western Svalbard that can be re-activated upon initial instability of the grounded, marine-based ice sheets. Analogous to this model, with the current acceleration of the Greenland ice melt, instabilities of existing methane reservoirs below and nearby the ice sheet are likely."); *and* Kleber G. E., Hodson A. J., Magerl L., Mannerfelt E. S., Bradbury H. J., Zhu Y., Trimmer M., & Turchyn A. V. (2023) *Groundwater springs formed during glacial retreat are a large source of methane in the high Arctic*, NAT. GEOSCI. 1–8, 5 ("Expected annual emissions from proglacial springs within the region range from 27 t yr^{-1} CH_4 (±0.14 t) to 230 t yr^{-1} CH_4 (±1.1 t), which equates to emissions of up to 37 kg km^{-2} yr^{-1} CH_4 (±2 kg km^{-2} yr^{-1} CH_4). When we extrapolate this across the Svalbard archipelago without accounting for regional differences in geology, methane emissions associated with proglacial groundwater springs could be up to 2.31 kt yr^{-1} CH_4 (±0.14 kt yr^{-1} CH_4).").

[616] Watts J. (27 October 2020) *Arctic methane deposits 'starting to release', scientists say*, THE GUARDIAN ("'At this moment, there is unlikely to be any major impact on global warming, but the point is that this process has now been triggered. This East Siberian slope methane hydrate system has been perturbed and the process will be ongoing,' said the Swedish scientist Örjan Gustafsson, of Stockholm University, in a satellite call from the vessel."), *discussing* the International Siberian Shelf Study (ISSS) 2020 Arctic Ocean Expedition. *See also* Smith E. (18 February 2020) *NASA Flights Detect Millions of Arctic Methane Hotspots*, National Aeronautics and Space Administration.

[617] Steinbach J., Holmstrand H., Shcherbakova K., Kosmach D., Brüchert V., Shakhova N., Salyuk A., Sapart C. J., Chernykh D., Noormets R., Semiletov I., & Gustafsson Ö. (2021) *Source apportionment of methane escaping the subsea permafrost system in the outer Eurasian Arctic Shelf*, PROC. NAT'L. ACAD. SCI. 118(10): 1–9, 7 ("Taken together, the triple-isotope data presented here, in combination with other system data and indications from earlier studies, suggest that deep thermogenic reservoirs are key sources of the elevated methane concentrations in the outer Laptev Sea. This finding is essential in several ways: The occurrence of elevated levels of radiocarbon-depleted methane in the water column may be an indication of thawing subsea permafrost in the study area (see also ref. 8). The triple-isotope fingerprinting suggests, however, that methane may not primarily originate directly from the subsea permafrost; the continuous leakage of an old geological reservoir to the water column suggests the existence of perforations in the subsea permafrost, serving as conduits of deeper methane to gas-charged shallow sediments. Second, the finding that methane is released from a large pool of preformed methane, as opposed to methane from slow decomposition of thawing subsea permafrost organic matter, suggests that these releases may be more eruptive in nature, which provides a larger potential for abrupt future releases."). *See also* Wild B., Shakhova N., Dudarev O.,

Ruban A., Kosmach D., Tumskoy V., Tesi T., Grimm H., Nybom I., Matsubara F., Alexanderson H., Jakobsson M., Mazurov A., Semiletov I., & Gustafsson Ö. (2022) *Organic matter composition and greenhouse gas production of thawing subsea permafrost in the Laptev Sea*, NAT. COMMUN. 13(5057): 1–12, 7 ("The lower rates of CH_4 production by subsea permafrost decomposition estimated here, and the likely oxidation of part of this CH_4, do not point to a dominant contribution of organic matter decomposition in thawed subsea permafrost to the high emissions observed in the area. We emphasize, however, the high variability of observed CH_4 production rates, and the limitations of upscaling from incubations to natural environments. Taken together, the high CH_4 emissions ubiquitously observed in the field likely stem from other sources such as preformed CH_4 in gas pockets in the subsea permafrost, collapsing CH_4 hydrates, or venting of a deep thermogenic CH_4 pool.").

[618] Dyonisius M. N., *et al.* (2020) *Old carbon reservoirs were not important in the deglacial methane budget*, SCIENCE 367(6480): 907–910, 908–909 ("Resulting CH_4 emissions from old permafrost carbon range from 0 to 53 Tg CH_4 per year (table S10) (20) throughout the last deglaciation and may have contributed up to 27% of the total CH_4 emissions to the atmosphere (95% CI upper limit) at the end of the OD-B transition (14.42 ka BP). However, we consider this calculation speculative (see section 4.3 of the materials and methods) (20)…. The last deglaciation serves only as a partial analog to current anthropogenic warming, with the most important differences being the much colder baseline temperature, lower sea level, and the presence of large ice sheets covering a large part of what are currently permafrost regions in the NH…. Because the relatively large global warming of the last deglaciation (which included periods of large and rapid regional warming in the high latitudes) did not trigger CH_4 emissions from old carbon reservoirs, such CH_4 emissions in response to anthropogenic warming also appear to be unlikely."). *See also* Canadell J. G., *et al.* (2021) *Chapter 5: Global Carbon and other Biogeochemical Cycles and Feedbacks*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 5-80 ("The present-day methane release from shelf clathrates is <10 $TgCH_4\ yr^{-1}$ (Kretschmer et al., 2015; Saunois et al., 2020). Despite polar amplification (Chapter 7), substantial releases from the permafrost-embedded subsea clathrates is very unlikely (Minshull et al., 2016; Malakhova and Eliseev, 2017, 2020). This is consistent with an overall small release of methane from the shelf clathrates during the last deglacial despite large reorganisations in climate state (Bock et al., 2017; Petrenko et al., 2017; Dyonisius et al., 2020). The long timescales associated with clathrate destabilisation makes it unlikely that CH_4 release from the ocean to the atmosphere will deviate markedly from the present-day value through the 21st century (Hunter et al., 2013), corresponding to no more than additional 20 ppb of atmospheric methane (i.e. <0.2 ppb yr^{-1} 52).").

[619] Malakhova V. V. & Eliseev A. V. (2024) *Subsea permafrost and associated methane hydrate stability zone: how long can they survive in the future?*, THEOR. APPL. CLIMATOL.: 1–19, 1 ("This Earth System Model was forced by idealized scenarios of CO_2 emissions and by changes of the parameters of the Earth's orbit … We found that at the other shelf, permafrost disappears either before the onset of the anthropogenic emissions or during a few centuries after it. In contrast, for the middle and shallow parts of the shelf, in the CO_2-emission forced runs, the subsea permafrost survive, at least, for 5 kyr after the emission onset or even for much longer. At the same parts of the self, methane hydrate stability. Zone (MHSZ) disappears not earlier than at 3 kyr after the CO_2 emission onset. … In general, the CO_2-induced warming in our simulations is able to enhance the pan-Arctic subsea permafrost loss severalfold during 1 kyr after the emissions onset, but it is less important for the respective MHSZ loss. The dynamics of MHSZ is largely independent on the chosen climate projection, at least for the next several thousand years.").

[620] Cheng L., *et al.* (2025) *Record High Temperatures in the Ocean in 2024*, ADV. ATMOS. SCI.: 1–18, 2 ("In 2024, both global sea surface temperature (SST) and upper 2000 m ocean heat content (OHC) reached unprecedented highs in the historical record. The 0–2000 m OHC in 2024 exceeded that of 2023 by 16 ± 8 ZJ (1 Zetta Joules = 1021 Joules, with a 95% confidence interval) (IAP/CAS data), which is confirmed by two other data products: 18 ± 7 ZJ (CIGAR-RT reanalysis data) and 40 ± 31 ZJ (Copernicus Marine data, updated to November 2024). The Indian Ocean, tropical Atlantic, Mediterranean Sea, North Atlantic, North Pacific, and Southern Ocean also experienced record-high OHC values in 2024. The global SST continued its record-high values from 2023 into the first half of 2024, and declined slightly in the second half of 2024, resulting in an annual mean of 0.61°C ± 0.02°C (IAP/CAS data) above the 1981–2010 baseline, slightly higher than the 2023 annual-mean value (by 0.07°C ± 0.02°C for IAP/CAS, 0.05°C ± 0.02°C

for NOAA/NCEI, and 0.06°C ± 0.11°C for Copernicus Marine). The record-high values of 2024 SST and OHC continue to indicate unabated trends of global heating.").

[621] Cheng L., Abraham J., Hausfather Z., & Trenberth K. E. (2019) *How fast are the oceans warming?*, SCIENCE 363(6423): 128–129, 128 ("About 93% of the energy imbalance accumulates in the ocean as increased ocean heat content (OHC)."). *See also* Intergovernmental Panel on Climate Change (2023) AR6 SYNTHESIS REPORT: CLIMATE CHANGE 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 11 ("It is virtually certain that the global upper ocean (0-700m) has warmed since the 1970s and extremely likely that human influence is the main driver. Ocean warming accounted for 91% of the heating in the climate system, with land warming, ice loss and atmospheric warming accounting for about 5%, 3% and 1%, respectively (*high confidence*)."); von Schuckmann K., *et. al.* (2023) *Heat stored in the Earth system 1960–2020: where does the energy go?,* EARTH SYST. SCI. DATA 15(4): 1675–1709, 1677 ("Here we show that the Earth system has continued to accumulate heat, with 381±61 ZJ accumulated from 1971 to 2020. This is equivalent to a heating rate (i.e., the EEI) of 0.48±0.1 W m^{-2}. The majority, about 89 %, of this heat is stored in the ocean, followed by about 6 % on land, 1 % in the atmosphere, and about 4 % available for melting the cryosphere. Over the most recent period (2006–2020), the EEI amounts to 0.76±0.2 W m^{-2}. The Earth energy imbalance is the most fundamental global climate indicator that the scientific community and the public can use as the measure of how well the world is doing in the task of bringing anthropogenic climate change under control. Moreover, this indicator is highly complementary to other established ones like global mean surface temperature as it represents a robust measure of the rate of climate change and its future commitment.").

[622] Solomon S., Daniel J. S., Sanford T. J., Murphy D. M., Plattner G.-K., Knutti R., & Friedlingstein P. (2010) *Persistence of climate changes due to a range of greenhouse gases*, PROC. NAT'L. ACAD. SCI. 107(43): 18354–18359, 18357 ("In the case of a gas with a 10-y lifetime, for example, energy is slowly stored in the ocean during the period when concentrations are elevated, and this energy is returned to the atmosphere from the ocean after emissions cease and radiative forcing decays, keeping atmospheric temperatures somewhat elevated for several decades. Elevated temperatures last longer for a gas with a 100-y lifetime because, in this case, radiative forcing and accompanying further ocean heat uptake continue long after emissions cease. As radiative forcing decays further, the energy is ultimately restored from the ocean to the atmosphere. Fig. 3 shows that the slow timescale of ocean heat uptake has two important effects. It limits the transfer of energy to the ocean if emissions and radiative forcing occur only for a few decades or a century. However, it also implies that any energy that is added to the ocean remains available to be transferred back to the atmosphere for centuries after cessation of emissions."). *See also* MacDougall A. H., *et al.* (2020) *Is there warming in the pipeline? A multi-model analysis of the Zero Emissions Commitment from* CO_2, BIOGEOSCI. 17(11): 2987–3016, 3003 ("Overall, the most likely value of ZEC on decadal timescales is assessed to be close to zero, consistent with prior work. However, substantial continued warming for decades or centuries following cessation of emissions is a feature of a minority of the assessed models and thus cannot be ruled out purely on the basis of models."); Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, REV. GEOPHYS. 61: 1–81, 55 (Figure 16); *and* Intergovernmental Panel on Climate Change (2023) AR6 SYNTHESIS REPORT: CLIMATE CHANGE 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 42 ("Sea level rise is unavoidable for centuries to millennia due to continuing deep ocean warming and ice sheet melt, and sea levels will remain elevated for thousands of years (*high confidence*).").

[626] Arias P. A., *et al.* (2021) *Technical Summary*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 74 ("It is *virtually certain* that the global ocean has warmed since at least 1971, representing about 90% of the increase in the global energy inventory (TS.3.1). The ocean is currently warming faster than at any other time since at least the last deglacial transition (*medium confidence*), with warming extending to

depths well below 2000 m (*very high confidence*). It is *extremely likely* that human influence was the main driver of ocean warming. Ocean warming will continue over the 21st century (*virtually certain*), and will *likely* continue until at least to 2300 even for low CO_2 emissions scenarios. Ocean warming is irreversible over centuries to millennia (*medium confidence*), but the magnitude of warming is scenario-dependent from about the mid-21st century (*medium confidence*) … Global mean SST has increased since the beginning of the 20th century by 0.88 [0.68 to 1.01] °C, and it is *virtually certain* it will continue to increase throughout the 21st century with increasing hazards to marine ecosystems (*medium confidence*). Marine heatwaves have become more frequent over the 20th century (*high confidence*), approximately doubling in frequency (*high confidence*) and becoming more intense and longer since the 1980s (*medium confidence*).").

[627] Wunderling N., Winkelmann R., Rockström J., Loriani S., Armstrong-McKay D., Ritchie P., Sakschewski B., & Donges J. (2023) *Global warming overshoots increase risks of climate tipping cascades in a network model*, NAT. CLIM. CHANG. 13: 75–82, 78–79 ("We define a high climate-risk zone as the region where the likelihood for no tipping event is smaller than 66% or the risk that one or more elements tip is higher than 33%. We compute this risk and find a marked increase for increasing convergence temperatures (compare Fig. 3d–f). For convergence temperatures of 1.5 °C and above, our results indicate that the high climate-risk zone spans the entire state space for final convergence temperatures of 1.5–2.0 °C. Only if final convergence temperatures are limited to or, better, below today's levels of global warming, while peak temperatures are below 3.0 °C, the tipping risks remain below 33% (Fig. 3d)…In the worst case of a convergence temperature of 2.0 °C (Fig. 3f), the tipping risk for at least one tipping event to occur is on the order of above 90% if peak temperatures of 4.0 °C are not prevented. The devastating negative consequences of such a scenario with high likelihood of triggering tipping events would entail notable sea-level rise, biosphere degradation or considerable North Atlantic temperature drops.").

[628] Dreyfus G. B., Xu Y., Shindell D., Zaelke D., & Ramanathan V. (2022) *Mitigating climate disruption in time: A self-consistent approach for avoiding both near-term and long-term global warming*, PROC. NAT'L. ACAD. SCI. 119(22): 1–8, 1 ("We find that mitigation measures that target only decarbonization are essential for strong long-term cooling but can result in weak near-term warming (due to unmasking the cooling effect of co-emitted aerosols) and lead to temperatures exceeding 2°C before 2050. In contrast, pairing decarbonization with additional mitigation measures targeting short-lived climate pollutants (SLCPs) and N_2O, slows the rate of warming a decade or two earlier than decarbonization alone and avoids the 2°C threshold altogether. These non-CO_2 targeted measures when combined with decarbonization can provide net cooling by 2030, reduce the rate of warming from 2030 to 2050 by about 50%, roughly half of which comes from methane, significantly larger than decarbonization alone over this timeframe.").

[629] Armstrong McKay D. I., Staal A., Abrams J. F., Winkelmann R., Sakschewski B., Loriani S., Fetzer I., Cornell S. E., Rockström J., & Lenton T. M. (2022) *Exceeding 1.5°C global warming could trigger multiple climate tipping points*, SCIENCE 377(6611): 1–10, 7 ("The chance of triggering CTPs is already non-negligible and will grow even with stringent climate mitigation (SSP1-1.9 in Fig. 2, B and C). Nevertheless, achieving the Paris Agreement's aim to pursue efforts to limit warming to 1.5°C would clearly be safer than keeping global warming below 2°C (90) (Fig. 2). Going from 1.5 to 2°C increases the likelihood of committing to WAIS and GrIS collapse near complete warm-water coral die-off, and abrupt permafrost thaw; further, the best estimate threshold for LABC collapse is crossed. The likelihood of triggering AMOC collapse, Boreal forest shifts, and extra-polar glacier loss becomes non-negligible at >1.5°C and glacier loss becomes likely by ~2°C. A cluster of abrupt shifts occur in ESMs at 1.5 to 2°C (19). Although not tipping elements, ASSI loss could become regular by 2°C, gradual permafrost thaw would likely become widespread beyond 1.5°C, and land carbon sink weakening would become significant by 2°C."). *See also* Lenton T. M., Rockstrom J., Gaffney O., Rahmstorf S., Richardson K., Steffen W., & Schellnhuber H. J. (2019) *Climate tipping points—too risky to bet against*, Comment, NATURE 575(7784): 592–595, 594 ("In our view, the clearest emergency would be if we were approaching a global cascade of tipping points that led to a new, less habitable, 'hothouse' climate state[11]. Interactions could happen through ocean and atmospheric circulation or through feedbacks that increase greenhouse-gas levels and global temperature. Alternatively, strong cloud feedbacks could cause a global tipping point[12,13].We argue that cascading effects might be common. Research last year[14] analysed 30 types of regime shift spanning physical climate and ecological systems, from collapse of the West Antarctic ice sheet to a switch from rainforest to savanna. This indicated that exceeding tipping points in one system can increase the risk of crossing them in others. Such links were found for 45% of possible interactions[14]. In our view, examples are starting to be observed.

… If damaging tipping cascades can occur and a global tipping point cannot be ruled out, then this is an existential threat to civilization. No amount of economic cost–benefit analysis is going to help us. We need to change our approach to the climate problem. … In our view, the evidence from tipping points alone suggests that we are in a state of planetary emergency: both the risk and urgency of the situation are acute….”); Steffen W., *et al.* (2018) *Trajectories of the Earth System in the Anthropocene*, PROC. NAT'L. ACAD. SCI. 115(33): 8252–8259, 8254 (“This analysis implies that, even if the Paris Accord target of a 1.5 °C to 2.0 °C rise in temperature is met, we cannot exclude the risk that a cascade of feedbacks could push the Earth System irreversibly onto a “Hothouse Earth” pathway. The challenge that humanity faces is to create a “Stabilized Earth” pathway that steers the Earth System away from its current trajectory toward the threshold beyond which is Hothouse Earth (Fig. 2). The human-created Stabilized Earth pathway leads to a basin of attraction that is not likely to exist in the Earth System's stability landscape without human stewardship to create and maintain it. Creating such a pathway and basin of attraction requires a fundamental change in the role of humans on the planet. This stewardship role requires deliberate and sustained action to become an integral, adaptive part of Earth System dynamics, creating feedbacks that keep the system on a Stabilized Earth pathway (Alternative Stabilized Earth Pathway).”); *and* Intergovernmental Panel on Climate Change (2023) AR6 SYNTHESIS REPORT: CLIMATE CHANGE 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 36, 42 (“In terrestrial ecosystems, 3–14% of the tens of thousands of species assessed will likely face a very high risk of extinction at a GWL of 1.5°C. Coral reefs are projected to decline by a further 70–90% at 1.5°C of global warming (*high confidence*). At this GWL, many low-elevation and small glaciers around the world would lose most of their mass or disappear within decades to centuries (*high confidence*). Regions at disproportionately higher risk include Arctic ecosystems, dryland regions, small island development states and Least Developed Countries (*high confidence*). … The likelihood of abrupt and irreversible changes and their impacts increase with higher global warming levels (*high confidence*). As warming levels increase, so do the risks of species extinction or irreversible loss of biodiversity in ecosystems such as forests (*medium confidence*), coral reefs (*very high confidence*) and in Arctic regions (*high confidence*). Risks associated with large-scale singular events or tipping points, such as ice sheet instability or ecosystem loss from tropical forests, transition to high risk between 1.5°C–2.5°C (*medium confidence*) and to very high risk between 2.5°C–4°C (*low confidence*). The response of biogeochemical cycles to anthropogenic perturbations can be abrupt at regional scales and irreversible on decadal to century time scales (*high confidence*). The probability of crossing uncertain regional thresholds increases with further warming (*high confidence*).”).

[630] Sun X., Wang P., Ferris T., Lin H., Dreyfus G., Gu B., Zaelke D., & Wang Y. (2022) *Fast Action on Short-lived Climate Pollutants and Nature-based Solutions to Help Countries Meet Carbon Neutrality Goals*, ADV. CLIM. CHANG. RES. 13: 564–577, 569 (“While more than 130 countries have committed to reaching net-zero emissions, only some of these jurisdictions include non-CO_2 pollutants in their pledges (Hale et al., 2021). As demonstrated by the summary of scientific studies above, countries need to include fast acting strategies on SLCPs and NbS in their climate policies to secure the most avoided warming on the way to meeting their carbon neutrality goals.”).

[631] United Nations (9 August 2021) *Guterres: The IPCC Report is a code red for humanity*, UN Regional Information Centre for Western Europe (“UN Secretary-General António Guterres says a report published today by the Intergovernmental Panel on Climate Change (IPCC) is a “code red for humanity. … The alarm bells are deafening, and the evidence is irrefutable: greenhouse gas emissions from fossil fuel burning and deforestation are choking our planet and putting billions of people at immediate risk,” the Secretary-General says in a statement.”).

[632] Intergovernmental Panel on Climate Change (2018) *Summary for Policymakers*, *in* GLOBAL WARMING OF 1.5 °C, *Special Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 4 (“Human activities are estimated to have caused approximately 1.0 ºC of global warming above pre-industrial levels, with a *likely* range of 0.8 ºC to 1.2 ºC. Global warming is *likely* to reach 1.5 ºC between 2030 and 2052 if it continues to increase at the current rate. (*high confidence*).”). In addition to cutting CO_2 emissions and emissions of the super climate pollutants, the IPCC 1.5 ºC Report also calculates the need for significant CO_2 removal. *Id.*, at 17 (“C.3. All pathways that limit global warming to 1.5°C with limited or no overshoot project the use of carbon dioxide removal (CDR) on the order of 100–1000 $GtCO_2$ over the 21st century.”).

[633] Xu Y. & Ramanathan V. (2017) *Well below 2 °C: Mitigation strategies for avoiding dangerous to catastrophic climate changes*, PROC. NAT'L. ACAD. SCI. 114(39): 10315–10323, 10319 ("Box 2. Risk Categorization of Climate Change to Society. … Warming of such magnitudes also has catastrophic human health effects. Many recent studies (**50**, **51**) have focused on the direct influence of extreme events such as heat waves on public health by evaluating exposure to heat stress and hyperthermia. It has been estimated that the likelihood of extreme events (defined as 3-sigma events), including heat waves, has increased 10-fold in the recent decades(**52**). Human beings are extremely sensitive to heat stress. For example, the 2013 European heat wave led to about 70,000 premature mortalities (**53**). The major finding of a recent study (**51**) is that, currently, about 13.6% of land area with a population of 30.6% is exposed to deadly heat. … According to this study, a 2 °C warming would double the land area subject to deadly heat and expose 48% of the population. A 4 °C warming by 2100 would subject 47% of the land area and almost 74% of the world population to deadly heat, which could pose existential risks to humans and mammals alike unless massive adaptation measures are implemented, such as providing air conditioning to the entire population or a massive relocation of most of the population to safer climates. … This bottom 3 billion population comprises mostly subsistent farmers, whose livelihood will be severely impacted, if not destroyed, with a one- to five-year megadrought, heat waves, or heavy floods; for those among the bottom 3 billion of the world's population who are living in coastal areas, a 1- to 2-m rise in sea level (likely with a warming in excess of 3°C) poses existential threat if they do not relocate or migrate. It has been estimated that several hundred million people would be subject to famine with warming in excess of 4 °C (**54**). However, there has essentially been no discussion on warming beyond 5 °C. Climate change-induced species extinction is one major concern with warming of such large magnitudes (>5°C). The current rate of loss of species is ∼1,000-fold the historical rate, due largely to habitat destruction. At this rate, about 25% of species are in danger of extinction in the coming decades (**56**). Global warming of 6°C or more (accompanied by increase in ocean acidity due to increased CO_2) can act as a major force multiplier and expose as much as 90% of species to the dangers of extinction (**57**). The bodily harms combined with climate change-forced species destruction, biodiversity loss, and threats to water and food security, as summarized recently (**58**), motivated us to categorize warming beyond 5°C as unknown??, implying the possibility of existential threats.").

[634] Steffen W., *et al.* (2018) *Trajectories of the Earth System in the Anthropocene*, PROC. NAT'L. ACAD. SCI. 115(33): 8252–8259, 8254, 8256 ("This risk is represented in **Figs. 1** and 2 by a planetary threshold (horizontal broken line in **Fig. 1** on the Hothouse Earth pathway around 2 °C above preindustrial temperature). Beyond this threshold, intrinsic biogeophysical feedbacks in the Earth System (***Biogeophysical Feedbacks***) could become the dominant processes controlling the system's trajectory. Precisely where a potential planetary threshold might be is uncertain (**15**, **16**). We suggest 2 °C because of the risk that a 2 °C warming could activate important tipping elements (**12**, **17**), raising the temperature further to activate other tipping elements in a domino-like cascade that could take the Earth System to even higher temperatures (***Tipping Cascades***). Such cascades comprise, in essence, the dynamical process that leads to thresholds in complex systems (section 4.2 in ref. **18**). This analysis implies that, even if the Paris Accord target of a 1.5 °C to 2.0 °C rise in temperature is met, we cannot exclude the risk that a cascade of feedbacks could push the Earth System irreversibly onto a "Hothouse Earth" pathway. … Hothouse Earth is likely to be uncontrollable and dangerous to many, particularly if we transition into it in only a century or two, and it poses severe risks for health, economies, political stability (**12**, **39**, **49**, **50**) (especially for the most climate vulnerable), and ultimately, the habitability of the planet for humans.").

[635] United Nations Environment Programme (2023) *One Atmosphere: An Independent Expert Review on Solar Radiation Modification Research and Deployment*, 1–38, 22 ("In the interests of academic freedom, it is suggested that no formal governance framework for SRM indoor research is required at this time. However, it would be advantageous to develop a set of norms or voluntary code of conduct that would promote reporting, transparency, inclusiveness and data-sharing. To govern small-scale outdoor SRM experiments or operational deployment of SRM systems, several existing frameworks could be relevant (Annex 5)… There is general agreement among this group of experts that governance of large-scale SAI deployment is valuable given the inherent risks associated with changing stratospheric conditions caused by large-scale interventions over long time periods (i.e. multiple decades). A broader framework for the governance of the stratosphere would address the changes that occur in the stratosphere from SAI experiments or deployment, and by other activities such as rocket launches, but might not address other concerns that are specific to SRM.").

[636] Forster P. M., et al. (2023) *Indicators of Global Climate Change 2022: annual update of large-scale indicators of the state of the climate system and human influence*, EARTH SYST. SCI. DATA 15(6): 2295–2327, 2308, 2309 ("Human-induced warming, also known as anthropogenic warming, refers to the component of observed global surface temperature increase over a specific period (for instance, from 1850–1900 as a proxy for pre-industrial climate to the last decade) attributable to both the direct and indirect effects of human activities, which are typically grouped as follows: well-mixed greenhouse gases (consisting of CO_2, CH_4, N_2O and F-gases) and other human forcings (consisting of aerosol–radiation interaction, aerosol–cloud interaction, black carbon on snow, contrails, ozone, stratospheric H_2O and land use) (Eyring et al., 2021). While total warming, the actual observed temperature change potentially resulting from both natural climate variability (internal variability of the climate system and the climate response to natural forcing) and human influences, is the quantity directly related to climate impacts and therefore relevant for adaptation, mitigation efforts focus on human-induced warming as the more relevant indicator for tracking progress against climate stabilisation targets. Further, as the attribution analysis allows human-induced warming to be disentangled from possible contributions from solar and volcanic forcing and internal variability (e.g. related to El Niño/La Nina events), it avoids misperception about short-term fluctuations in temperature. … AR6 defined the current human-induced warming relative to the 1850–1900 baseline as the decade average of the previous 10-year period (see AR6 WGI Chap. 3). This paper provides an update of the 2010–2019 period used in the AR6 to the 2013–2022 decade. SR1.5 defined current human-induced warming as the average of a 30-year period centred on the current year, assuming the recent rate of warming continues (see SR1.5 Chap. 1). This definition is currently almost identical to the present-day single-year value of human-induced warming, differing by about 0.01 ◦C (see results in Sect. 7.4); the attribution assessment in SR1.5 was therefore provided as a single-year warming."); 2297 ("In AR6 WGI and here, reaching a level of global warming is defined as the global surface temperature change, averaged over a 20-year period, exceeding a particular level of global warming, for example, 1.5 ◦C global warming. Given the current rates of change and the likelihood of reaching 1.5 ◦C of global warming in the first half of the 2030s (Lee et al., 2021, 2023; Riahi et al., 2022), it is important to have robust, trusted and also timely climate indicators in the public domain to form an evidence base for effective science-based decision-making."). However, the averaging periods and definitions used vary, with many meteorological services not differentiating the human-induced component from total warming. See for example Coperniuc Climate Services, *Global Temperature Trends Monitor*, (last visited 18 August 2023) (""Global warming" at a point in time refers to the increase in a 30-year average, centred on the specified time, of Earth's global surface temperature relative to the pre-industrial period[.]").

[637] Copernicus Climate Change Service (10 January 2025) *Global Climate Highlights 2024* ("2024 was 0.72°C warmer than the 1991–2020 average, and 1.60°C warmer than the pre-industrial level, making it the first calendar year to exceed 1.5°C above that level."). Note that different international organizations measure the temperature anomaly against different pre-industrial datasets, leading to small variations between the temperatures reported by different agencies; for other estimates, *see* National Oceanic and Atmospheric Administration (10 January 2025) *2024 was the world's warmest year on record* ("In 2024, global temperature exceeded the pre-industrial (1850–1900) average by 2.63 degrees F (1.46 degrees C)."); Rohde R. (10 January 2025) *Global Temperature Report for 2024*, Berkeley Earth ("The global annual average for 2024 in our dataset is estimated as 1.62 ± 0.06 °C (2.91 ± 0.11 °F) above the average during the period 1850 to 1900, which is traditionally used a reference for the pre-industrial period."); World Meteorological Organization (10 January 2025) *WMO confirms 2024 as warmest year on record at about 1.55°C above pre-industrial level* ("The global average surface temperature was 1.55 °C (with a margin of uncertainty of ± 0.13 °C) above the 1850-1900 average, according to WMO's consolidated analysis of the six datasets."); *and* Madge G. (10 January 2025) *2024: record-breaking watershed year for global climate*, Met Office ("The global average temperature for 2024 was 1.53±0.08°C above the 1850-1900 global average, according to the HadCRUT5 temperature series, collated by the Met Office, the University of East Anglia and the National Centre for Atmospheric Science."). For additional data points from other international organizations tracking temperature, *see* Hausfather Z. (10 January 2025) *State of the climate: 2024 sets a new record as the first year above 1.5C*, CARBON BRIEF.

[638] World Meteorological Organization (June 2024) WMO GLOBAL ANNUAL TO DECADAL CLIMATE UPDATE 2024-2028, 7 ("Annual mean global near-surface temperature for each year in this five-year period is predicted to be between 1.1°C and 1.9°C (90% confidence interval) higher than the period 1850-19001. The chance of the annual mean global near-surface temperature in 2024-2028 exceeding 1.5°C above 1850-1900 levels for at least one year is 80% and is

increasing with time (brown histogram and righthand axis in Figure 4). It is as likely as not (47% chance) that the five-year mean will exceed this threshold.").

[639] Forster P. M., *et al.* (2024) *Indicators of Global Climate Change 2023: annual update of key indicators of the state of the climate system and human influence*, EARTH SYST. SCI. DATA 16(6): 2625–2658, 2637 ("The change from 1850–1900 to 2004–2023 was 1.05 [0.90–1.16] °C, 0.07 °C higher than the value reported in AR6 WGI from 3 years earlier.").

[640] World Meteorological Organization (2025) STATE OF THE GLOBAL CLIMATE 2024, 22 (Figure 11 shows "IPCC AR6 method warming [centered] at 2019 Average of previous 10 years, 2015-2024").

[641] Intergovernmental Panel on Climate Change (2021) *Summary for Policymakers*, in CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., et al. (eds.), SPM-5 ("Each of the last four decades has been successively warmer than any decade that preceded it since 1850. Global surface temperature in the first two decades of the 21st century (2001-2020) was 0.99 [0.84-1.10] °C higher than 1850-1900[9]…. Global surface temperature was 1.09 [0.95 to 1.20] °C higher in 2011–2020 than 1850–1900, with larger increases over land (1.59 [1.34 to 1.83] °C) than over the ocean (0.88 [0.68 to 1.01] °C). The estimated increase in global surface temperature since AR5 is principally due to further warming since 2003–2012 (+0.19 [0.16 to 0.22] °C). Additionally, methodological advances and new datasets contributed approximately 0.1ºC to the updated estimate of warming in AR6[10]."… [Footnote 10:] "Since AR5, methodological advances and new datasets have provided a more complete spatial representation of changes in surface temperature, including in the Arctic. These and other improvements have additionally increased the estimate of global surface temperature change by approximately 0.1 ºC, but this increase does not represent additional physical warming since the AR5.").

[642] Forster P. M., et al. (2024) *Indicators of Global Climate Change 2023: annual update of key indicators of the state of the climate system and human influence*, EARTH SYST. SCI. DATA 16(6): 2625–2658, 2639 ("In this 2024 update, we assess the 2014–2023 decade average human-induced warming at 1.19 [1.0 to 1.4] °C, which is 0.12 °C above the AR6 assessment for 2010–2019."). See also Intergovernmental Panel on Climate Change (2021) *Summary for Policymakers*, in CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Masson-Delmotte V., et al. (eds.), SPM-5 ("The likely range of total human-caused global surface temperature increase from 1850–1900 to 2010–2019 [11] is 0.8°C to 1.3°C, with a best estimate of 1.07°C. It is likely that well-mixed GHGs contributed a warming of 1.0°C to 2.0°C, other human drivers (principally aerosols) contributed a cooling of 0.0°C to 0.8°C, natural drivers changed global surface temperature by –0.1°C to 0.1°C, and internal variability changed it by –0.2°C to 0.2°C. It is very likely that well-mixed GHGs were the main driver[12] of tropospheric warming since 1979, and extremely likely that human-caused stratospheric ozone depletion was the main driver of cooling of the lower stratosphere between 1979 and the mid-1990s." … Footnote 11: "The period distinction with A.1.2 arises because the attribution studies consider this slightly earlier period. The observed warming to 2010–2019 is 1.06 [0.88 to 1.21] °C." … Footnote 12: "Throughout this SPM, 'main driver' means responsible for more than 50% of the change.").

[643] Forster P. M., et al. (2024) *Indicators of Global Climate Change 2023: annual update of key indicators of the state of the climate system and human influence*, EARTH SYST. SCI. DATA 16(6): 2625–2658, 2642–2643 ("For the purpose of providing annual updates, we take the median estimate at a precision of 0.01 °C per decade, resulting in an overall best estimate for 2014-2023 of 0.26 °C per decade. This increased rate relative to the AR6 assessment of 0.2 °C per decade is broken down in the following way: (i) 0.03 °C per decade of the increase is from a change in rounding precision (updating the AR6 assessment for the 2010–2019 warming rate from 0.2 °C per decade to 0.23 °C per decade), (ii) 0.02 °C per decade of the increase is due to methodological and dataset updates (updating the 2010–2019 warming rate from 0.23 °C per decade to 0.25 °C per decade; this includes the effect of adding 4 additional observed years, which affects the attribution for the entire historical period), and (iii) only 0.01 °C per decade of the increase is due to a substantive increase in rate for the 2014–2023 period since the 2010–2019 period (updating 0.25 °C per decade for 2010–2019 to 0.26 °C per decade for 2014–2023).").

[644] Xu Y., Ramanathan V., & Victor D. G. (2018) *Global warming will happen faster than we think*, NATURE 564(7734): 30–32, 31 ("In 2017, industrial carbon dioxide emissions are estimated to have reached about 37 gigatonnes[2]. This puts them on track with the highest emissions trajectory the IPCC has modelled so far. This dark news means that the next 25 years are poised to warm at a rate of 0.25–0.32 °C per decade[3]. That is faster than the 0.2 °C per decade that we have experienced since the 2000s, and which the IPCC used in its special report.").

[645] Forster P. M., et al. (2024) *Indicators of Global Climate Change 2023: annual update of key indicators of the state of the climate system and human influence*, EARTH SYST. SCI. DATA 16(6): 2625–2658, 2640 ("WGI AR6 found that, averaged for the 2010–2019 period, essentially all observed global surface temperature change was human-induced, with solar and volcanic drivers and internal climate variability making a negligible contribution. This conclusion remains the same for the 2014–2023 period. Generally, whatever methodology is used, on a global scale, the best estimate of the human-induced warming is (within small uncertainties) similar to the observed global surface temperature change (Table 6).").

[646] Forster P. M., et al. (2024) *Indicators of Global Climate Change 2023: annual update of key indicators of the state of the climate system and human influence*, EARTH SYST. SCI. DATA 16(6): 2625–2658, 2639 ("The single-year-average human-induced warming is assessed to be 1.31 [1.1 to 1.7] °C in 2023 relative to 1850–1900. This best estimate for the current level of human-induced warming reaches the 1.3 °C threshold for the first time.").

[647] Arias P. A., et al. (2021) *Technical Summary*, in CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Masson-Delmotte V., et al. (eds.), 42 ("Timing of crossing 1.5°C global warming: Slightly different approaches are used in SR1.5 and in this Report. SR1.5 assessed a likely range of 2030 to 2052 for reaching a global warming level of 1.5°C (for a 30-year period), assuming a continued, constant rate of warming. In AR6, combining the larger estimate of global warming to date and the assessed climate response to all considered scenarios, the central estimate of crossing 1.5°C of global warming (for a 20-year period) occurs in the early 2030s, ten years earlier than the midpoint of the likely range assessed in the SR1.5, assuming no major volcanic eruption. (TS.1.3, Cross-Section Box TS.1)"). See also Lee J.-Y., Marotzke J., Bala G., Cao L., Corti S., Dunne J. P., Engelbrecht F., Fischer E., Fyfe J. C., Jones C., Maycock A., Mutemi J., Ndiaye O., Panickal S., & T. Zhou (2021) *Chapter 4: Future Global Climate: Scenario-Based Projections and Near-Term Information*, in CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Masson-Delmotte V., et al. (eds.), 555 ("The threshold-crossing time is defined as the midpoint of the first 20-year period during which the average GSAT exceeds the threshold. In all scenarios assessed here except SSP5-8.5, the central estimate of crossing the 1.5°C threshold lies in the early 2030s. This is in the early part of the likely range (2030–2052) assessed in the IPCC Special Report on Global Warming of 1.5°C (SR1.5), which assumed continuation of the then-current warming rate; this rate has been confirmed in the AR6. Roughly half of this difference between assessed crossing times arises from a larger historical warming diagnosed in AR6. The other half arises because for central estimates of climate sensitivity, most scenarios show stronger warming over the near term than was assessed as 'current' in SR1.5 (medium confidence)."). Emphasis added.

[648] Trewin B. (2022) *Assessing Internal Variability of Global Mean Surface Temperature From Observational Data and Implications for Reaching Key Thresholds*, J. GEOPHYS. RES. ATMOS. 127(23): 1–9, 7 ("This indicates that, providing there is no major change in the underlying warming rate, the probability that 1.5°C has been crossed on or before the current year is substantially above 50% once the observed mean for the most recent 11 years reaches 1.43°C. The probability is about 90% once the 11-year mean reaches 1.44°C, while crossing is unlikely to have occurred if the observed 11-year mean is below 1.40°C."). *See also* Betts R. A., Belcher S. E., Hermanson L., Klein Tank A., Lowe J. A., Jones C. D., Morice C. P., Rayner N. A., Scaife A. A., & Stott P. A. (2023) *Approaching 1.5 °C: how will we know we've reached this crucial warming mark?*, NATURE 624(7990): 33–35, 35 ("We propose a new indicator — the 20-year average temperature rise centred around the current year. This is estimated by blending observations for the past 10 years with climate model projections or forecasts for the next 10 years, and taking an average over the combined 20-year period….projections or forecasts could use the IPCC's assessed warming rates[8] and the WMO's

decadal forecasts. Researchers will need to decide which pathway of future greenhouse-gas and aerosol concentrations should be used for the central estimate of the forecast.”).

[649] United Nations Environment Programme (2024) [Emissions Gap Report 2024], 34 (*see* “Figure 4.2 Projections of global warming under the pledge-based scenarios assessed in this chapter” showing “Unconditional NDCs continuing” with a projection of 2.6°C [1.8–3.4°C] for a 50% chance.).

[650] Intergovernmental Panel on Climate Change (2023) [AR6 Synthesis Report: Climate Change 2023], *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 33 (“Modelled pathways consistent with the continuation of policies implemented by the end of 2020 lead to global warming of 3.2 [2.2-3.5]°C (5–95% range) by 2100 (medium confidence) (see also Section 2.3.1). Pathways of >4°C (≥50%) by 2100 would imply a reversal of current technology and/or mitigation policy trends (medium confidence). However, such warming could occur in emissions pathways consistent with policies implemented by the end of 2020 if climate sensitivity or carbon cycle feedbacks are higher than the best estimate (high confidence).”).

[651] Hansen J. E., et al. (2023) *[Global warming in the pipeline]*, Oxf. Open Clim. Change 3(1): 1–33, 7 (“If ECS is 4°C (1°C per W/m^2), more warming is in the pipeline than widely assumed. GHG forcing today already exceeds 4 W/m^2. Aerosols reduce the net forcing to about 3 W/m^2, based on IPCC estimates (Section 5), but warming still in the pipeline for 3 W/m^2 forcing is 1.8°C, exceeding warming realized to date (1.2°C). Slow feedbacks increase the equilibrium response even further (Summary section). Large warmings can be avoided via a reasoned policy response, but definition of effective policies will be aided by an understanding of climate response time.”); 21 (“With current policies, we expect climate forcing for a few decades post-2010 to increase 0.5-0.6 W/m^2 per decade and produce global warming at a rate of at least +0.27°C per decade. In that case, global warming should reach 1.5°C by the end of the 2020s and 2°C by 2050 (Fig. 24).”; Figure 24 caption reads “Edges of the predicted post-2010 accelerated warming rate (see text) are 0.36 and 0.27°C per decade.”); 1 (“Equilibrium global warming for today’s GHG amount is 10°C, which is reduced to 8°C by today’s human-made aerosols. Equilibrium warming is not ‘committed’ warming; rapid phaseout of GHG emissions would prevent most equilibrium warming from occurring. However, decline of aerosol emissions since 2010 should increase the 1970–2010 global warming rate of 0.18°C per decade to a post-2010 rate of at least 0.27°C per decade. Thus, under the present geopolitical approach to GHG emissions, global warming will exceed 1.5°C in the 2020s and 2°C before 2050. Impacts on people and nature will accelerate as global warming increases hydrologic (weather) extremes.”). *See also* Hansen J., Sato M., Ruedy R., & Simons L. (13 October 2023) *[El Nino Fizzles. Planet Earth Sizzles. Why?]*, Columbia University, 3 (“The El Nino thus provides a crude measure of possible acceleration of global warming. A 50% acceleration of the long-term (1970-2010) global warming rate (0.18°C per decade) is shown by the lower edge of the yellow region in Fig. 2, while the upper edge is 100% acceleration to 0.36°C per decade….Much of the aerosol pollution arises from fossil fuels, so, as the world moves to clean energies, aerosol amounts should decline and unmask the GHG warming that had been compensated by aerosol cooling. (We long ago described this aerosol cooling as a Faustian bargain, and later discussed it in more detail.) Thus, for the next few decades – barring purposeful actions to reduce Earth’s energy imbalance – we expect the global warming rate will be accelerated to at least the rate (50% increase) of the lower boundary of the yellow area.”).

[652] Judd E. J., Tierney J. E., Lunt D. J., Montañez I. P., Huber B. T., Wing S. L., & Valdes P. J. (2024) *[A 485-million-year history of Earth’s surface temperature]*, Science 385(6715): eadk3705, 6 (“With CO_2 plotted in $\log_2$ space, the slope of the linear regression between CO_2 and GMST indicates a change in GMST of 7.7° ± 0.3°C per doubling of CO_2 (1s; based on York regression (86), which accounts for errors in both CO_2 and GMST). This value is consistent across the Cenozoic (8.2° ± 0.4°C; fig. S13A), the Paleozoic (7.8° ± 1.5°C; fig. S12B), and the Cenozoic and Paleozoic combined (8.0° ± 0.4°C; fig. S12C). We call this metric, which quantifies the long-term response of GMST to CO_2, the “apparent” Earth system sensitivity (AESS). Like traditional ESS (10), AESS includes both fast (e.g., clouds and sea ice) and slow (e.g., ice sheet growth and decay) climate feedbacks. However, it also implicitly assumes that the impact of changes in solar luminosity, paleogeography, non-CO_2 greenhouse gases, or other forcings compensate for each other in some way (as explored above). For these reasons, AESS is not comparable with conventional ECS, which the IPCC AR6 reports is 2° to 5°C for the modern climate (7). However, the PhanDA AESS value agrees well

with (and is more directly comparable to) CO_2-only ESS estimates spanning the past 10 million years (also 8°C) (11) and the past 800 thousand years (7° to 13°C) (12, 13). Unlike some modeling studies, which have indicated that climate sensitivity increases at higher GMST (61, 81, 87), we do not observe a statistically robust state dependency in AESS in either the Cenozoic or Paleozoic, at least on the stage level. Further work is needed to understand why the AESS value is so consistent across the Phanerozoic, and what determines its ~8°C magnitude.").

[654] Intergovernmental Panel on Climate Change (2021) *Summary for Policymakers*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), SPM-10 ("It is *virtually certain* that hot extremes (including heatwaves) have become more frequent and more intense across most land regions since the 1950s, while cold extremes (including cold waves) have become less frequent and less severe, with *high confidence* that human-induced climate change is the main driver[14] of these changes. Some recent hot extremes observed over the past decade would have been *extremely unlikely* to occur without human influence on the climate system. Marine heatwaves have approximately doubled in frequency since the 1980s (*high confidence*), and human influence has *very likely* contributed to most of them since at least 2006."). *See also* Kotz M., Wenz L., & Levermann A. (2021) *Footprint of greenhouse forcing in daily temperature variability*, PROC. NAT'L. ACAD. SCI. 118(32): 1–8, 1 ("Assessing historical changes to daily temperature variability in comparison with those from state-of-the-art climate models, we show that variability has changed with distinct global patterns over the past 65 years, changes which are attributable to rising concentrations of greenhouse gases. If these rises continue, temperature variability is projected to increase by up to 100% at low latitudes and decrease by 40% at northern high latitudes by the end of the century.").

[655] World Weather Attribution (14 May 2024) *Climate change made the deadly heatwaves that hit millions of highly vulnerable people across Asia more frequent and extreme* ("Throughout April and continuing into May 2024, extreme record-breaking heat led to severe impacts across the Asian continent. From Israel, Palestine, Lebanon and Syria, in the West, to Myanmar, Thailand, Vietnam and the Philippines in the East, large regions of Asia experienced temperatures well above 40°C for many days.").

[656] World Weather Attribution (14 May 2024) *Climate change made the deadly heatwaves that hit millions of highly vulnerable people across Asia more frequent and extreme* ("To estimate the influence that human-caused climate change has had on extreme heat in West Asia and the Philippines, we combine climate models with observations. Observations and models both show a strong increase in likelihood and intensity. In the Philippines, the change in likelihood is so large that the event would have been impossible without human-caused climate change. In West Asia, climate change increased the probability of the event by about a factor of 5. … In South Asia, a region that we have studied twice in the last two years, our analysis was simpler and based only on observations. Similarly to what we found in previous studies, we observe a strong climate change signal in the 2024 April mean temperature. We find that these extreme temperatures are now about 45 times more likely and 0.85ºC hotter. These results align with our previous studies, where we found that climate change made the extreme heat about 30 times more likely and 1ºC hotter.").

[657] Ahmed M. (23 May 2024) *Hundreds of people suffer heatstroke in Pakistan, and dangerous heat is forecast to stay a while*, ASSOCIATED PRESS ("Doctors treated hundreds of victims of heatstroke at hospitals across Pakistan on Thursday after an intense heat wave sent temperatures above normal levels due to climate change, officials said. Temperatures soared as high as 49 degrees Celsius (120 degrees Fahrenheit) the previous day in Mohenjo Daro.)."

[658] World Weather Attribution (21 March 2024) *Dangerous humid heat in southern West Africa about 4°C hotter due to climate change* ("The southern coastal zone of Western Africa – also called the Guinea zone – experienced abnormal early season heat in February 2024. A combination of high temperatures and relatively humid air resulted in area average Heat Index values of about 50°C, which is classified to be in the 'danger' level that is associated with a high risk of heat cramps and heat exhaustion. Locally, values even entered the level of 'extreme danger' that is associated with high risk of heat stroke, with values up to 60°C (fig. 1)."), *discussing* Pinto I., et al. (2024) DANGEROUS HUMID HEAT IN SOUTHERN WEST AFRICA ABOUT 4°C HOTTER DUE TO CLIMATE CHANGE, World Weather Attribution.

[659] World Weather Attribution (21 March 2024) *Dangerous humid heat in southern West Africa about 4°C hotter due to climate change* ("We find that because of human-induced climate change, the area-averaged heat index is in today's world about 4°C higher in today's 1.2°C warmer climate. Also, such humid heat has become much more likely, it is at least 10 times more likely in today's world."), *discussing* Pinto I., et al. (2024) DANGEROUS HUMID HEAT IN SOUTHERN WEST AFRICA ABOUT 4°C HOTTER DUE TO CLIMATE CHANGE, World Weather Attribution.

[660] Blunden J. & Boyer T. (eds.) (2024) *State of the Climate in 2023*, BULL. AMER. METEOR. SOC. 105(8): Si-S484, S55 ("The year 2023 emerged as a record-breaking year by a considerable margin for humid heat over global land, based on daily maximum wet-bulb temperatures (T_wX), for all but one (T_wX31) of the six indices presented herein (see Table 2.6 for definitions of these indices). … The annual T_wX90p anomaly (Fig. 2.26b), a measure of local extremes, was 26.4 days year^{-1} above average, far exceeding the previous record of 16.2 days year^{-1} in 1998."); *see* Figure 2.26b for rates of change for T_wX90p, showing a trend of 4.83±1.24 additional days year^{-1} decade^{-1}, which would provide an added ~12 days per year that exceed the 90th percentile of the climatological daily maximum wet-bulb temperature.

[661] Thompson A. (7 September 2023) *Half the World's Population Faced Extreme Heat for at Least 30 Days This Summer*, SCIENTIFIC AMERICAN ("A new analysis by the nonprofit organization Climate Central finds that more than 3.8 billion people were exposed to extreme heat that was worsened by human-caused climate change from June through August, and at least 1.5 billion experienced such heat every day of that period. … The organization's worldwide temperature analysis during this year's Northern Hemisphere summer found 48 percent of the world's population experienced at least 30 days of extreme heat that was made at least three times more likely by climate change, and at least 1.5 billion people experienced heat at that level or higher for the entire summer. Many of those people were in areas closer to the equator, such as the Caribbean, northern Africa and Southeast Asia.").

[662] Copernicus Climate Change Service (27 July 2023) *July 2023 sees multiple global temperature records broken* ("The month started with the daily global mean surface air temperature record being broken on four days in a row, from 3-6 July. All days since then have been hotter than the previous record of 16.80°C, set on 13 August 2016. The hottest day was 6 July, when the global average temperature reached 17.08°C, and the values recorded on 5 and 7 July were within 0.01°C of this. This means that the first three weeks of the month was the warmest three-week period on record. During the first and third weeks, temperatures also temporarily exceeded the 1.5°C threshold above preindustrial level – a limit set in the Paris Agreement. ERA5 data also show that the global mean surface air temperature for the first 23 days of July was 16.95°C. This is well above the 16.63°C recorded for the full month of July 2019, which is the current hottest July and hottest month in the ERA5 record. It is almost certain that, in due course, data will show July 2023 to break both these records."). *See also* Climate Reanalyzer (13 July 2023) *Daily 2-meter Air Temperature*, Climate Change Institute, University of Maine; *and* World Meteorological Organization (27 July 2023) *July 2023 is set to be the hottest month on record*, Press Release.

[663] World Weather Attribution (25 July 2023) *Extreme heat in North America, Europe and China in July 2023 made much more likely by climate change* ("In line with what has been expected from past climate projections and IPCC reports these events are not rare anymore today. North America, Europe and China have experienced heatwaves increasingly frequently over the last years as a result of warming caused by human activities, hence the current heat waves are not rare in today's climate with an event like the currently expected approximately once every 15 years in the US/Mexico region, once every 10 years in Southern Europe, and once in 5 years for China. Without human induced climate change these heat events would however have been extremely rare. In China it would have been about a 1 in 250 year event while maximum heat like in July 2023 would have been virtually impossible to occur in the US/Mexico region and Southern Europe if humans had not warmed the planet by burning fossil fuels. In all the regions a heatwave of the same likelihood as the one observed today would have been significantly cooler in a world without climate change. Similar to previous studies we found that the heatwaves defined above are 2.5°C warmer in Southern Europe, 2°C warmer in North America and about 1°C in China in today's climate than they would have been if it was not for human-induced climate change."). *See also* Climate Central (14 December 2023), *Record Global Temperatures and U.S. Billion-Dollar Disasters* ("During 2023's record-hottest summer (June - August), nearly half of the world's population experienced 30 or more days with hot temperatures made at least three times more likely by human-caused

climate change. … Climate Central analysis found that 97% of the U.S. population experienced at least one summer day with hot temperatures made at least 2x more likely due to human-caused climate change.”).

[664] World Meteorological Association (30 November 2023) *2023 shatters climate records, with major impacts* (“Extreme heat affected many parts of the world. Some of the most significant were in southern Europe and North Africa, especially in the second half of July where severe and exceptionally persistent heat occurred. Temperatures in Italy reached 48.2 °C, and record-high temperatures were reported in Tunis (Tunisia) 49.0 °C, Agadir (Morocco) 50.4 °C and Algiers (Algeria) 49.2 °C.”).

[665] World Weather Attribution (21 December 2022) *Climate change made record breaking early season heat in Argentina and Paraguay about 60 times more likely* (“The 2022 heatwave has led to large-scale power outages, wildfires and, in combination with the ongoing drought, poor harvests. It is estimated to have led to an increase in heat-related deaths, with the impacts unequally distributed across In different cities and municipalities across South America, people living in some areas – often poorer neighbourhoods – experience higher temperatures than others, as they lack green space, adequate thermal insulation from heat, electricity, shade, and water which can be lifelines during heatwaves…. We find that human-caused climate change made the event about 60 times more Alternatively, a heatwave with a similar probability would be about 1.4°C less hot in a world that had not been warmed by human activities.”), *discussing* Rivera J. A., *et al.* (2022) CLIMATE CHANGE MADE RECORD BREAKING EARLY SEASON HEAT IN ARGENTINA AND PARAGUAY ABOUT 60 TIMES MORE LIKELY, World Weather Attribution.

[666] World Meteorological Organization (2023) STATE OF THE CLIMATE IN LATIN AMERICA AND THE CARIBBEAN 2022, No. 1322, 17 (“The prolonged dry conditions associated with high temperatures led to record wildfires in January and February in Argentina and Paraguay. There was an increase of 283% and 258%, respectively, in the number of hotspots detected when compared to the 2001–2021 average.61 From January to March 2022, wildfire emissions were the highest in the last 20 years in Paraguay and northern Argentina.”).

[667] Harrington L. J., Ebi K. L., Frame D. J., & Otto F. E. L. (2022) *Integrating attribution with adaptation for unprecedented future heatwaves*, CLIM. CHANGE 172(2): 1–7, 3 (“Thus, specifically resolving whether a recent heatwave — say, one which occurs once per decade in today’s climate — would have occurred either once in 100 generations or once in 1000 generations in a pre-industrial climate, is no longer useful. When the current climate has changed so significantly that the pre-industrial world becomes a poor basis of comparison, other tools are needed to instead quantify future changes in exposure or the effectiveness of adaptation to changes in extreme weather seen over recent decades.”), *discussed in* Sengupta S. (3 May 2022) *An extraordinary heat wave exposes the limits of protecting people*, THE NEW YORK TIMES (“For more than a month now, across much of the country (and in next door Pakistan), temperatures have soared and stayed there. The capital, Delhi, topped 46 degrees Celsius (114 degrees Fahrenheit) last week. West Bengal, in the muggy east of the country, where my family is from, is among those regions where the combination of heat and humidity could rise to a threshold where the human body is in fact at risk of cooking itself. That theoretical limit is a “wet bulb” temperature — when a thermometer is wrapped in a wet cloth, accounting for both heat and humidity — of 35 degrees Celsius. In neighboring Pakistan, the Meteorological Department warned last week that daily high temperatures were 5 to 8 degrees Celsius above normal, and that in the mountainous north, fast-melting snow and ice could cause glacial lakes to burst. How much of this extreme heat can be blamed on climate change? That’s now becoming an “obsolete question,” Friederike Otto, a leader in the science of attributing extreme weather events to climate change, said in a paper published Monday. The rise in the average global temperature has already intensified heat waves “many times faster than any other type of extreme weather,” the paper concluded. Get used to extremes. Adapt. As much as possible.”); *and* Tunio Z. (7 May 2022) *An unprecedented heat wave in India and Pakistan is putting the lives of more than a billion people at risk*, INSIDE CLIMATE NEWS. *See also* Copernicus Climate Change Services (7 July 2022) *Heatwaves grip parts of Europe, Asia and North America in the first half of 2022* (“The second heatwave in this analysis, covering Pakistan and northwestern India, is the longest and the most impactful, in terms of the number of people directly affected. A series of warm spells impacted nearly 2 billion people throughout the whole season; some areas are still experiencing exceptional temperatures as of mid-June, with the most anomalous temperatures observed in northeastern India, and the monsoon approaching northwestern India more slowly than usual.”).

[668] Alizadeh M. R., Abatzoglou J. T., Adamowski J. F., Prestemon J. P., Chittoori B., Akbari Asanjan A., & Sadegh M. (2022) *Increasing Heat-Stress Inequality in a Warming Climate*, EARTH'S FUTURE 10(2): 1–11, 6 ("In the 2010s, the low-income region observed over 30% more heatwave days as compared to the high-income region (average of 13.2 vs. 10.0 days per year; Data Set S1). The low-income region also observed the highest rate of increase in the mean annual heatwave season length among all per-capita GDP clusters in the past four decades, with 23.8 additional days in the 2010s versus the 1980s (as compared to 14.4 days in the high-income region; Figure 3; Data Set S1)."); 7 ("Furthermore, the low-income region is expected to experience almost as much exposure to heatwaves in the 2090s as the other three-quartiles of the world combined (mean annual heatwave exposure of 19.8 vs. 21.5 billion person-days per year for the low-income region and the rest of the world, respectively; Figure S6 in Supporting Information S1), raising notable heat-stress inequality concerns (Herold et al., 2017; Mitchell & Chakraborty, 2015)."). *See also* Zaelke D. & Dreyfus G. (19 July 2022) *Can we beat the heat — or is this the beginning of the end?*, THE HILL ("Acclimatization may allow some to adapt to higher temperatures. But the rapid increase in heat extremes in regions with no prior history of them will test our collective ability to adapt, especially as global warming shifts climates out of the range that nurtured the development of human civilization. … We now see the future of climate change more clearly because it's already here. Punishing heatwaves are roaming the planet, from the U.S., to India and South Asia, to China and Europe: global warming is making them more frequent, more severe and longer lasting.").

[669] Philip S. Y., *et al.* (2021) *Rapid attribution analysis of the extraordinary heatwave on the Pacific Coast of the US and Canada*, WORLD WEATHER ATTRIBUTION, 26 ("In this study, the influence of human-induced climate change on the intensity and probability of the Pacific Northwest heatwave of 2021 was investigated. We analysed the heat in the area 45 ◦N–52 ◦N, 119 ◦W–123 ◦W that includes the cities Vancouver, Seattle and Portland. Based on the analysis of annual maximum daily maximum temperatures in weather observations and modeling, we conclude that the occurrence of a heatwave of the intensity experienced in that area would have been virtually impossible without human-caused climate change. Such an event is estimated to be a one in 1000-yr event in the current climate and would have been at least 150 times rarer without human-induced climate change. Also, this heatwave was about 2 ◦C (1.2 ◦C to 2.8 ◦C) hotter due to human induced climate change. Looking into the future to a world with 2 ◦C of global warming, an event like this, currently estimated to occur only once every 1000 years, would occur roughly every 5 to 10 years.").

[670] Iles C. E., Samset B. H., Sandstad M., Schuhen N., Wilcox L. J., & Lund M. T. (2024) *Strong regional trends in extreme weather over the next two decades under high- and low-emissions pathways*, NAT. GEOSCI. 17(9): 845–850, 849 ("Under SSP5–8.5, almost 70% of the world's current population will experience unprecedented joint rates of change of both indices combined, 83% very unusual and 91% unusual. Even under strong mitigation (SSP1–2.6) 20% of the world's population will experience joint rates larger than 2 s.d. of PI [pre-industrial] trends, 60% >1.5 s.d. and 77% >1 s.d. A large proportion of population will experience unprecedented (21%), highly unusual (73%) or unusual (89%) rates of change in temperature extremes under SSP5–8.5. This proportion reduces under strong mitigation but still reaches 38% and 75% for highly unusual and unusual rates of change, respectively.").

[671] Iles C. E., Samset B. H., Sandstad M., Schuhen N., Wilcox L. J., & Lund M. T. (2024) *Strong regional trends in extreme weather over the next two decades under high- and low-emissions pathways*, NAT. GEOSCI. 17(9): 845–850, 849 (see Table 1 "Percentage of the world's population affected by strong rates of change of climate extremes in the next 20 years").

[672] Iles C. E., Samset B. H., Sandstad M., Schuhen N., Wilcox L. J., & Lund M. T. (2024) *Strong regional trends in extreme weather over the next two decades under high- and low-emissions pathways*, NAT. GEOSCI. 17(9): 845–850, 848 ("Under SSP5–8.5, more than a third of land regions experience joint changes >2 s.d. for the 2021–2040 period. The regions are clustered at lower latitudes and often contain low-income countries that are particularly vulnerable to the impacts of climate change, exacerbating the climate risk from this compound hazard. Southern Asia and the Arabian Peninsula are projected to see these unprecedented joint changes also under SSP1–2.6. If we weaken the criterion to 1 s.d. of PI [pre-industrial] variability, almost all regions experience such joint near-term changes under SSP5–8.5, and most also under SSP1–2.6 (Fig. 3f)."); 849 ("Almost all regions also experience changes in rates of TXx of >1 s.d. in at least one scenario, and parts of Africa, northern South America, western central Asia, the Arabian

Peninsula and southern Europe experience changes of >2 s.d. These latter are regions with low trend variability (Supplementary Fig. 17) and correspond well to the regions experiencing the earliest emergence of (absolute) mean and extreme temperature changes from interannual variability[18–22].").

673 First Street Foundation (2022) THE 6TH NATIONAL RISK ASSESSMENT: *HAZARDOUS HEAT*, 4 ("The results indicate that the incidence of extreme heat is growing across the country, both in absolute and relative terms. In absolute terms, the incidence of heat that exceeds the threshold of the National Weather Service's (NWS) highest category for heat, called "Extreme Danger" (Heat Index above 125°F) is expected to impact about 8 million people this year, increasing to about 107 million people in 2053, an increase of 13 times over 30 years. This increase in "Extreme Danger Days" is concentrated in the middle of the country, in areas where there are no coastal influences to mitigate extreme temperatures."), *discussed in* Kaufman L. (15 August 2022) *Much of the US Will Be an 'Extreme Heat Belt' by the 2050s*, BLOOMBERG.

674 United Nations (2024) *Secretary-General's Call to Action on Extreme Heat*, 7 ("The world's cities are heating up at twice the global average rate due to rapid urbanization and the urban heat island effect.[17] Heatwaves present an acute danger to urban centres, where structural, socio-economic, and demographic factors magnify their impacts. Urban areas house more than half of the world's population, and another two and a half billion people could be added to urban areas by 2050.[18] As the world is heating up faster than anticipated, cities are bearing the brunt, as congestion, the built environment and concentrated energy use trap and amplify temperatures.").

675 United Nations (2024) *Secretary-General's Call to Action on Extreme Heat*, 7 ("Layering city locations over IPCC models[19] shows many cities becoming places where extreme temperatures persist for nearly half the year. At 1.5°C of warming, 67 cities will experience 150 or more days a year of temperatures exceeding 35°C. Under 3°C of warming, it rises to 197 cities.[20] The impacts of extreme heat will not be evenly shared between or within cities, and addressing thermal inequality is an urgent challenge. Between 1.5°C and 2°C of global warming, the most appreciable temperature rises will occur in the tropics, which house a disproportionate amount of people living below poverty lines.[21] By 2050, studies project "a 700 per cent global increase in the number of urban poor living in extreme-heat conditions, with the largest increases across West Africa and South-East Asia."[22]").

676 Vecellio D. J., Kong Q., Kenney W. L., & Huber M. (2023) *Greatly enhanced risk to humans as a consequence of empirically determined lower moist heat stress tolerance*, PROC. NAT'L. ACAD. SCI. 120(42): 1–9, 7 ("Results showed that a large majority of the hours of uncompensable heat stress will occur at Ta less than 40 ◦C (50% RH or above), providing evidence that humid heatwaves will be an increasing danger in future climates (27, 43). However, as noted, climate models have a proclivity for underestimating extreme events, meaning extreme hot, dry heatwaves, perhaps exacerbated by compound local drought and subsequent land-atmosphere interactions, may be a larger factor in future heat stress than what current projections show (44, 45)."); 8 ("Therefore, Tw thresholds in this paper consist of a constant 30.58 °C when Ta ≤ 40 °C, which is deemed a "humid" hot-hour. From there, critical Tw decreases in a linear fashion with increasing Ta and decreasing RH given the increasing impact of dry heat gain and sweating limitations. Thus, any threshold exceedance above Ta = 40 °C is considered "nonhumid" (as moderate RHs may not be considered "dry")."); 5 ("However, nonhumid conditions leading to threshold exceedance are more significant in other parts of the world. The Arabian Peninsula is projected to experience an increase in nonhumid hours of threshold exceedance in a 2 °C warmer world. By the time of a projected GMST increase of 4 °C, nonhumid person-hours of threshold exceedance are expected to be greater than 11 billion, making up more than one-quarter of all person-hours of threshold exceedance (Fig. 3E). North America, which does not experience significant exceedance of the heat stress threshold until 3 °C GMST increase, experiences the largest proportion of nonhumid days of uncompensability with 23.8% of person hours at 3 °C and 31.8% at 4 °C (Fig. 3F)."); 2-3 ("With increased global warming, the regions that will experience the first moist heat waves and subsequent substantial increases in accumulated hothours per year are also the regions with the largest concentrations of the world's population, specifically, those in India and the Indus River Valley (population: 2.2 billion), eastern China (population: 1.0 billion), and sub-Saharan Africa (population: 0.8 billion) (Fig. 1E).").

677 Freychet N., Hegerl G. C., Lord N. S., Lo Y. T. E., Mitchell D., & Collins M. (2022) *Robust increase in population exposure to heat stress with increasing global warming*, ENVIRON. RES. LETT. 17(6): 1–10, 4 ("If global mean

temperature reaches +3 ◦C above pre-industrial levels, about 45% of the total population could be exposed each year to severe heat stress (TW = 27.5 ◦C), with an exposure (see section 2.5) reaching around 5 billions."); 5 ("Limiting global temperature increase to +1.5 or +2 ◦C would still lead to about 20% or 30% of the total population exposed to severe conditions, respectively. On the other hand, if following the SSP370 scenario to the end of the century, more than half of humanity could be exposed each year to severe heat stress."). *See also* Lenton T. M., Xu C., Abrams J. F., Ghadiali A., Loriani S., Sakschewski B., Zimm C., Ebi K. L., Dunn R. R., Svenning J.-C., & Scheffer M. (2023) *Quantifying the human cost of global warming*, NAT. SUSTAIN. 6(10): 1237–1247, 4 ("We now focus on a future world of 9.5 billion. When assessing risk it is important to consider worst-case scenarios. If the transient climate response to cumulative emissions is high, current policies could, in the worst case, lead to ~3.6 °C end-of-century global warming (as projected under SSP3-7.0; Extended Data Table 1). This results in 34 ± 10% (3.3 ± 0.9 billion) hot exposed. … Overall, going from ~2.7 °C global warming under current policies to meeting the Paris Agreement 1.5 °C target reduces hot exposure from 22 to 5% (2.1 to 0.4 billion; Fig. 3a). … Thus, each 0.3 °C decline in end-of-century warming reduces hot exposure by 4.3% or 410 million people."); *and* Mora C., *et al.* (2017) *Global risk of deadly heat*, NAT. CLIM. CHANGE 7(7): 501–506, 503–504 ("We found that by 2100, even under the most aggressive mitigation scenario (that is, RCP 2.6), ~26.9% (±8.7% s.d.) of the world's land area will be exposed to temperature and humidity conditions exceeding the deadly threshold by more than 20 days per year, exposing ~47.6% (±9.6% s.d.) of the world's human population to deadly climates (using Shared Socioeconomic Pathways projections of future human population relevant to each of the CMIP5 RCPs, see Methods). Scenarios with higher emissions will affect an even greater percentage of the global land area and human population. By 2100, ~34.1% (±7.6% s.d.) and ~47.1% (±8.9% s.d.) of the global land area will be exposed to temperature and humidity conditions that exceed the deadly threshold for more than 20 days per year under RCP 4.5 and RCP 8.5, respectively; this will expose ~53.7% (±8.7% s.d.) and ~73.9% (±6.6% s.d.) of the world's human population to deadly climates by the end of the century (Fig. 2, extended results in Supplementary Fig. 4).").

[678] Nelson G. C., Vanos J., Havenith G., Jay O., Ebi K. L., & Hijmans R. J. (2024) *Global reductions in manual agricultural work capacity due to climate change*, GLOB. CHANGE BIOL. 30(1): 1–14, Table 2 ("Share of agricultural workers in the recent past during the crop growing season with mean growing season physical work capacity (PWC) at or below a cutoff value of PWC by period and emission scenario. The total number of workers (856.7 million) is based on the mean of estimates for 2018–2020."); 12 ("Some global locations are already experiencing significant losses in PWC during periods when a large share of crops is grown. Parts of the Amazon region in Brazil, West and East Central Africa, much of South and Southeast Asia, and parts of eastern China already see growing season losses of PWC of 0.2 to 0.3. With the thermal conditions that would prevail at end-century with the SSP5-8.5 scenario, average PWC values in these regions decline by as much as an additional 0.3. Regions with minimal present-day heat stress impacts could experience significant losses, including the southeast United States, much of southern South America, large areas in Africa, and more northerly areas in China. Without adaptation, labor output would be reduced in large parts of the world.").

[679] Masuda Y. J., Parsons L. A., Spector J. T., Battisti D. S., Castro B., Erbaugh J. T., Game E. T., Garg T., Kalmus P., Kroeger T., Mishra V., Shindell D., Tigchelaar M., Wolff N. H., & Zeppetello L. R. V. (2024) *Impacts of warming on outdoor worker well-being in the tropics and adaptation options*, ONE EARTH 7(3): 1–19, 5 ("To quantify population exposure with 1C of global warming, we used 2001–2020 climate data and 2010 population statistics. We estimated approximately 1% of the population (range due to interannual climate variability: 0.06%–2.35%) resides in places where heavy work needed to be restricted for over half of the year's hours (Figure 3D). This corresponds to approximately 8 million people (range: 3–141 million) with significant lost work time in the last decade. Population exposure in the tropics substantially increases at 2C of global warming (assuming moderate population growth under Shared Socioeconomic Pathway 2 [SSP2] in 2050), with about 13% of the population (range due to interannual variability: 8.4%–21.2%), or approximately 797 million people (range: 505–1,273 million), located in areas where heavy work should be limited for over half of the hours in the year (Figure 3D). Countries with particularly severe impact under additional global warming include Bahrain, Cambodia, Pakistan, Qatar, and the UAE, which are projected to lose up to 10%–15% of labor productivity by about 3C of global warming.[72] In terms of economic (GDP) losses, humid heat is projected to most strongly impact countries in tropical West Africa and South and Southeast Asia, with some countries showing losses equivalent to 3%–5% of GDP.[72]").

[680] United Nations (2024) *Secretary-General's Call to Action on Extreme Heat*, 12 ("In 1995, the economic loss due to heat stress at work was US$280 billion.[42] That figure is rising as temperatures increase, with expectations that economic losses will reach US$2.4 trillion in 2030. This is 2.2 per cent of total working hours worldwide – a loss equivalent to 80 million full-time jobs.[43] Further, heat exposure-related loss in labour capacity resulted in average potential income losses equivalent to US$863 billion in 2022.[44] Implementing occupational, safety and health (OSH) measures to prevent occupational injuries related to excessive heat could save over US$361 billion globally. At the regional and country level, this ranges from 0.004 per cent of GDP in Europe and Central Asia to 0.1 per cent in Africa, with some countries experiencing national GDP losses exceeding 1.5 per cent. Notably, the largest national cost burden is observed in low- and lower-middle-income economies.[45]").

[681] Vecellio D. J., Kong Q., Kenney W. L., & Huber M. (2023) *Greatly enhanced risk to humans as a consequence of empirically determined lower moist heat stress tolerance*, PROC. NAT'L. ACAD. SCI. 120(42): 1–9, 3 ("In this study's worst-case scenario of a 4 ◦C warmer world, around 2.7 billion persons will experience at least 1 wk of daytime (8 h) ambient conditions associated with uncompensable heat stress, 1.5 billion will experience a month under such conditions, and 363.7 million will be faced with an entire season (3 mo) of life-altering extreme heat (Fig. 1F).").

[682] United Nations (2024) *Secretary-General's Call to Action on Extreme Heat*, 7 ("The impacts of extreme heat will not be evenly shared between or within cities, and addressing thermal inequality is an urgent challenge. Between 1.5°C and 2°C of global warming, the most appreciable temperature rises will occur in the tropics, which house a disproportionate amount of people living below poverty lines.").

[683] Zhang Y., Held I., & Fueglistaler S. (2021) *Projections of tropical heat stress constrained by atmospheric dynamics*, NAT. GEO. 14(3): 133–137, 133 ("For each 1 °C of tropical mean warming, global climate models project extreme TW (the annual maximum of daily mean or 3-hourly values) to increase roughly uniformly between 20° S and 20° N latitude by about 1 °C. This projection is consistent with theoretical expectation based on tropical atmospheric dynamics, and observations over the past 40 years, which gives confidence to the model projection. For a 1.5 °C warmer world, the probable (66% confidence interval) increase of regional extreme TW is projected to be 1.33–1.49 °C, whereas the uncertainty of projected extreme temperatures is 3.7 times as large. These results suggest that limiting global warming to 1.5 °C will prevent most of the tropics from reaching a TW of 35 °C, the limit of human adaptation.").

[684] Lenton T. M., Xu C., Abrams J. F., Ghadiali A., Loriani S., Sakschewski B., Zimm C., Ebi K. L., Dunn R. R., Svenning J.-C., & Scheffer M. (2023) *Quantifying the human cost of global warming*, NAT. SUSTAIN. 1–11, calculated based on Supplementary Data 1, 1, 5–6 ("Country-level results for population, land area and land fraction exposed to MAT > 29°C … By end-of-century (2080–2100), current policies leading to around 2.7 °C global warming could leave one-third (22–39%) of people outside the niche. Reducing global warming from 2.7 to 1.5 °C results in a ~5-fold decrease in the population exposed to unprecedented heat (mean annual temperature ≥29 °C). The lifetime emissions of ~3.5 global average citizens today (or ~1.2 average US citizens) expose one future person to unprecedented heat by end-of-century. That person comes from a place where emissions today are around half of the global average. These results highlight the need for more decisive policy action to limit the human costs and inequities of climate change. … Assuming a future world of 9.5 billion, India has the greatest population exposed under 2.7 °C global warming, >600 million, but this reduces >6-fold to ~90 million at 1.5 °C global warming. Nigeria has the second largest population exposed, >300 million under 2.7 °C global warming, but this reduces >7-fold to 20-fold, from ~100 million under 2.7 °C global warming to 80 million exposed under 2.7 °C global warming, there are even larger proportional reductions at 1.5 °C global warming. Sahelian–Saharan countries including Sudan (sixth ranked) and Niger (seventh) have a ~2-fold reduction in exposure, because they still have a large fraction of land area hot exposed at 1.5 °C global warming (Fig. 5b). The fraction of land area exposed approaches 100% for several countries under 2.7 °C global warming (Fig. 5b). Brazil has the greatest absolute land area exposed under 2.7 °C global warming,") despite almost no area being exposed at 1.5 °C, and Australia and India also experience massive increases in absolute area exposed (Fig. 4). (If the future population reaches 11.1 billion, the ranking of countries by population exposed remains similar, although the numbers exposed increase.) Those most exposed under 2.7 °C global warming come from nations that today are above the median poverty rate and below the median per capita emissions (Fig. 6)."). *See also* Xu C., Kohler T. A., Lenton T. M., Svenning J.-C., & Scheffer M. (2020) *Future of the human climate niche*,

PROC. NAT'L. ACAD. SCI. 117(21): 11350–11355, 11352 ("Such a calculation suggests that for the RCP8.5 business-as-usual climate scenario, and accounting for expected demographic developments (the SSP3 scenario[15]),∼3.5 billion people (roughly 30% of the projected global population; SI Appendix, Fig. S12) would have to move to other areas if the global population were to stay distributed relative to temperature the same way it has been for the past millennia (SI Appendix, Fig. S13). Strong climate mitigation following the RCP2.6 scenario would substantially reduce the geographical shift in the niche of humans and would reduce the theoretically needed movement to ∼1.5 billion people (∼13% of the projected global population; SI Appendix, Figs. S12 and S13).").

[685] Friedlingstein P., *et al.* (2025) *Global Carbon Budget 2024*, EARTH SYST. SCI. DATA 17(3): 965–1039, 994 ("Current CO_2 concentrations in the atmosphere are unprecedented for the last 2 million years, and the current rate of atmospheric CO_2 increase is at least 10 times faster than at any other time during the last 800 000 years (Canadell et al., 2021).").

[686] Curran J. C. & Curran S. A. (2025) *Natural sequestration of carbon dioxide is in decline: climate change will accelerate*, WEATHER 80(3): 85–87, 86 ("It is immediately evident from Figure 2 that natural sequestration, drawing down atmospheric CO2 during the Northern Hemisphere summer, increased for many years and reached a peak, estimated here as occurring in 2008, but is now declining.").

[687] Friedlingstein P., *et al.* (2025) *Global Carbon Budget 2024*, EARTH SYST. SCI. DATA 17(3): 965–1039, 1000 ("The negative effect of climate can be seen across the globe and is particularly strong in most of South America, Central America, the southwestern USA, central Europe, the western Sahel, southern Africa, Southeast Asia and southern China, and eastern Australia (Fig. 12b). Globally, over the 2014–2023 period, climate change reduces the land sink by 0.87 ± 0.56 GtC yr^{-1} (27 % of S_{LAND}).").

[688] Lee C., Song H., Choi Y., Cho A., & Marshall J. (2025) *Observed multi-decadal increase in the surface ocean's thermal inertia*, NAT. CLIM. CHANG. 15(3): 308–314, 313 ("These upper-ocean changes suggest a trend towards increased heat storage in the upper ocean and reduced sequestration into its interior, and an increasing likelihood of prolonged heatwaves and hence a threat to near-surface marine ecosystems.").

[689] von Schuckmann K., *et al.* (2023) *Heat stored in the Earth system 1960–2020: where does the energy go?*, EARTH SYST. SCI. DATA 15(4): 1675–1709, 1693 ("The estimate of heat storage in all Earth system components not only allows for obtaining a measure of how much and where heat is available for inducing changes in the Earth system (Fig. 1) but also to improve the accuracy of the Earth system's total heat gain. In 1971–2020 and for the total heat gain, the ocean accounts for the largest contributor with an about 89 % fraction of the global inventory."). *See also* National Aeronautics & Space Administration (*last updated* December 2024) *Ocean Warming* ("Ninety percent of global warming is occurring in the ocean, causing the water's internal heat to increase since modern recordkeeping began in 1955…").

[690] Friedlingstein P., *et al.* (2025) *Global Carbon Budget 2024*, EARTH SYST. SCI. DATA 17(3): 965–1039, 969 ("The remaining carbon budget for a 50 % likelihood to limit global warming to 1.5, 1.7, and 2 °C above the 1850–1900 level has been reduced to 65 GtC (235 $GtCO_2$), 160 GtC (585 $GtCO_2$), and 305 GtC (1110 $GtCO_2$), respectively, from the beginning of 2025, equivalent to around 6, 14, and 27 years, assuming 2024 emissions levels.").

[691] Hausfather Z. (8 October 2018) *Analysis: Why the IPCC 1.5C report expanded the carbon budget*, CARBON BRIEF ("Even the revised 1.5C carbon budget is unlikely to be the end of the debate, however, given a number of large remaining uncertainties. These include: The precise meaning of the 1.5C target. Disagreement about what "surface temperature" actually refers to. The definition of the "pre-industrial" period. What observational temperature datasets should be used. What happens to non-CO_2 factors that influencing the climate. Whether Earth-system feedbacks like thawing permafrost are taken into account. Finally, the emission scenarios considered in the new SR15 also tend to emit far more than the budget would allow, but make up for it with the large-scale use of negative emissions in the future. The large carbon budget uncertainty and reliance on negative emissions – basically, sucking CO_2 from the atmosphere and permanently storing it – suggest that the idea of a carbon budget may be of limited use for strict mitigation targets such as 1.5C.").

[692] Forster P. M., et al. (2023) *Indicators of Global Climate Change 2022: annual update of large-scale indicators of the state of the climate system and human influence*, EARTH SYST. SCI. DATA 15(6): 2295–2327, 2312–2313 ("The RCB for limiting warming to 1.5 °C is becoming very small. It is important, however, to correctly interpret this information. RCB estimates consider projected reductions in non-CO_2 emissions that are aligned with a global transition to net zero CO_2 emissions. These estimates assume median reductions in non-CO_2 emissions between 2020–2050 of CH_4 (50 %), N_2O (25 %) and SO_2 (77 %)."); 2313 ("Table 7. Updated estimates of the remaining carbon budget for 1.5, 1.7 and 2.0 ◦C, for five levels of likelihood, considering only uncertainty in TCRE.").