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

Critical Role of Short-lived Super Climate Pollutants To Address the Climate Emergency

Background Note

14 June 2023

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About the Institute for Governance & Sustainable Development (IGSD)

IGSD’s mission is to build resilience by accelerating fast climate mitigation actions to slow near-term warming and self-amplifying climate feedbacks, avoid or at least delay catastrophic climate and 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 (CO₂) emissions from decarbonizing the energy system with the sprint to rapidly cut non-CO₂ super climate pollutants and protect carbon sinks. The super climate pollutants include four short-lived climate pollutants (SLCPs)—methane (CH₄), hydrofluorocarbons (HFCs), black carbon soot, and tropospheric ozone (O₃)—as well as the longer-lived nitrous oxide (N₂O).

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 adapt to unavoidable changes and build resilience. 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 decade or two 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 CO₂ 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 approaches 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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1. **Introduction and summary**

This *Background Note* summarizes the science supporting the need for fast climate mitigation to slow warming in the near term (2023–2041). It focuses on the importance of cutting super climate pollutants and protecting carbon sinks to slow self-amplifying feedbacks and avoid, or at least delay, irreversible tipping points. It also explains why winning a fast mitigation sprint to 2030 is critical for addressing the climate emergency and how the sprint complements the marathon to decarbonize the economy and achieve net-zero emissions by 2050 or earlier.

Climate change presents two challenges, or races, that we must simultaneously run and win: the race to stabilize the climate in the longer term, and the race to slow the rate of warming in the near term to reduce the risk of climate extremes that scale with the rate of warming and threaten to accelerate self-amplifying feedbacks and trigger a cascade of irreversible tipping points. Cutting super climate pollutants, in particular the short-lived climate pollutants (SLCPs)—black carbon, methane (CH₄), tropospheric ozone, and hydrofluorocarbons (HFCs)—can avoid four times more warming at 2050 than cutting CO₂ only, and reduce projected warming in the Arctic by two-thirds and the rate of global warming by half. Reducing climate risks and staying within the limits to adaptation are critical to building resilience.

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

The window for effective mitigation to slow self-amplifying feedbacks and avoid, or at least delay, irreversible tipping points is shrinking to perhaps 10 years or less, including the window to prevent crashing through the 1.5 °C guardrail. At 2 °C, of warming the risks of triggering “relatively large, abrupt and sometimes irreversible changes in systems” become high, according to the Intergovernmental Panel on Climate Change’s (IPCC) 6th Assessment Report (AR6).4

- Because extreme climate impacts depend on the *rate of warming* as well as the total warming, the accelerating rate of increases in CO₂ and other warming climate pollutants is particularly troubling.5
- Continuing record climate emissions mean that the rate of warming could increase from 0.2 °C per decade to 0.25–0.32 °C per decade over the next 25 years.6
- The 2011–2020 temperature average was 1.1 °C higher than the 1850-1900 average while the average over land was nearly 1.6 °C (1.59 °C) higher during the same time period.7 The global average surface temperatures in 2022 was 0.86 °C warmer than the 20th century average, which is 1.06 °C warmer than 1880-1900 average,8 and 1.2 °C higher than 1850–1900 average.9
  - According to the National Oceanic and Atmospheric Administration, “[t]he ten warmest January–September periods on record [since 1880] have occurred since 2010.”10
  - The 20-year global average surface temperature could exceed the 1.5 °C guardrail by the early 2030s and 2 °C by 2050 or sooner due to rising emissions, declining particulate air pollution that unmasks existing warming, and natural climate variability (Figure 1).11
  - There is a 66% chance that annual average near-surface global temperatures will exceed 1.5 °C for at least one year between 2023 and 2027 and a 32% chance that the five-year mean from 2023–2027 will exceed this threshold, according to the
World Meteorological Organization.\textsuperscript{12} As the triple La Niña ends, warmer El Niño conditions could push 2023 to the warmest year on record\textsuperscript{13} and 2024 to 1.4–1.5 °C.\textsuperscript{14}

**Figure 1. Projected warming**

![Graph showing projected warming since 1850-1900 (°C) with a note: 1.5 °C of warming occurs a decade earlier than projected by the IPCC.](image)

- The concentration of climate pollutants in the atmosphere continues to increase at record rates despite the pandemic and economic slowdown.
  - In 2022, the global average atmospheric concentration of CO₂ was a record 417.06 parts per million (“ppm”). The 2.13 ppm increase between 2021 and 2022 was the 11\textsuperscript{th} consecutive year where the amount of CO₂ increased by more than 2 ppm. The rate of increase in CO₂ over the past 60 years is nearly 100 times faster than previous natural increases, including those that occurred at the end of the last ice age 11,000-17,000 years ago.\textsuperscript{15} For comparison, in the 1990s the average increase of CO₂ was 1.5 ppm/year.\textsuperscript{16}
  - In September 2021, atmospheric methane concentrations exceeded 1,900 parts per billion (ppb) for the first time.\textsuperscript{17} The annual growth rates set records in 2020 (15 ppb/year) and 2021 (18 ppb/year) for the fastest rates of increase since records started in 1983, more than double the 2007–2019 average (7.3 ppb/year).\textsuperscript{18} Recent studies have attributed this surge of atmospheric methane concentrations to increasing emissions from wetlands and a reduced capacity of the atmosphere to remove methane.\textsuperscript{19} Methane concentrations increased by 14 ppb in 2022 to reach an average of 1,912 ppb, more than two and a half times pre-industrial levels.\textsuperscript{20}
  - N₂O concentrations grew by 1.24 ppb to 335.7 ppb in 2022, representing a 24% increase over pre-industrial levels. The highest growth rates recorded occurred in 2020 and 2021.\textsuperscript{21}
  - Today the Earth is trapping twice as much heat as it did in 2005, with loss of reflective sea ice and changes in clouds contributing significantly to the extra heat the planet is now retaining.\textsuperscript{22}

Anthropogenic changes to the climate are on track to exceed the natural variability of the past 66 million years and is accelerating a transition towards a quasi-stable climate state characterized by extreme weather events.\textsuperscript{23}

Even at 1.2 °C of global warming in 2021–2022,\textsuperscript{24} weather extremes are becoming more frequent and more severe.\textsuperscript{25} 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.”\textsuperscript{26}

- The record-breaking June 2021 heatwave in the Pacific Northwest (U.S. and Canada) would have been virtually impossible absent human-caused climate change\textsuperscript{27} and would have been much less detrimental to human health.\textsuperscript{28} The probability of such heatwaves will increase by up to 200 times by the 2040s, occurring every 5 to 10 years, given our current emissions trajectory.\textsuperscript{29}

- Global warming made the 2019 heatwaves in Western Europe up to 100 times more likely.\textsuperscript{30} As Europe sizzled under another heatwave in 2021, the Mediterranean region was evolving into a “wildfire hotspot.”\textsuperscript{31}

- Heatwaves in Europe are increasing in frequency and intensity faster than in most of the planet due to a warming climate and changes in the jet stream.\textsuperscript{32} In July 2022, climate change made the record-breaking 40 °C (104 °F) in the UK at least 10-times more likely.\textsuperscript{33} The record-breaking heatwaves will be considered an “average” summer in Europe by 2035, even if current climate commitments are met.\textsuperscript{34}

- With unprecedented long-duration heatwaves afflicting over a billion people in India and Pakistan in 2022, scientists note that “the current climate has changed so significantly that the pre-industrial world becomes a poor basis of comparison.”\textsuperscript{35}

- Night-time fire intensity has increased globally by 7.2% in the last two decades due to rising temperatures, causing more intense, longer-lasting, and larger fires.\textsuperscript{36}

- The catastrophic flooding inundated a third of Pakistan in 2022 was very likely made more severe by climate change, increasing rainfall, glacier melt, and extending a La Niña event in the Pacific for a rare third year.\textsuperscript{37}

- The eastern coast of South Africa saw extreme flooding in 2022, which affected 40,000 people and caused US $1.57 billion in property damage. A recent study shows that the probability of such extreme rainfall in the region has doubled due to human-induced climate change.\textsuperscript{38}

- 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, placing it on the “extreme danger level” of the National Weather Service’s heat index.\textsuperscript{39}

The probability of “record-shattering” extreme climate events increases with the rate of warming and is thus pathway-dependent,\textsuperscript{40} while the frequency and intensity of extreme events scale with warming levels.\textsuperscript{41}

Under current policies, global temperatures are on track to reach 3.2 °C [2.2–3.5 °C] by the end of the century; if climate sensitivity or climate feedbacks are higher, warming levels could exceed 4 °C.\textsuperscript{42} (The preprint from 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 and eventually would reach an equilibrium warming of 8–10 °C in later centuries.\textsuperscript{43})
B. Only a dual assault on CO₂ and super climate pollutants, particularly methane, would make it possible for the world to keep 1.5 °C in sight and stay below 2 °C

- The CO₂ and super climate pollutant strategies are complementary and not exchangeable. Achieving 2050 Net Zero CO₂ targets is essential for stabilizing the climate by the end of the century due to the long lifetime of CO₂ in the atmosphere but it cannot, by itself, prevent global temperatures from exceeding 1.5 °C above pre-industrial levels, the guardrail beyond which the world’s climate is expected to pass irreversible tipping points.⁴⁴
  - The recent AR6 reports confirm that cutting fossil fuel emissions—the main source of CO₂—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 aerosols, which act to cool the climate. These cooling sulfates fall out of the atmosphere fast, while CO₂ lasts much longer, thus leading to overall warming for the first decade or two.⁴⁵
  - The International Energy Agency report, *Credible Pathways to 1.5 °C: Four Pillars for Action in the 2020s*, also recognizes that “tackling non-CO₂ emissions is vital to limiting peak warming. Assuming strong action on CO₂, meeting or exceeding commitments like the Kigali Amendment on HFCs and the Global Methane Pledge, and acting on non-CO₂ 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.”⁴⁶
- In addition to zeroing out CO₂ emissions to curb long-term warming, it is essential to slow near-term warming by reducing SLCPs—methane (CH₄), black carbon (BC) soot, tropospheric ozone (O₃), and HFCs. (These short-lived pollutants are often referred to as “super climate pollutants” because of their potency and ability to quickly reduce warming. Nitrous oxide (N₂O) is also a super climate pollutant but is not short-lived.)
- Reducing SLCPs is the only currently known mitigation strategy that can cut the rate of warming in the near-term, slow self-amplifying feedbacks, and avoid or at least delay irreversible tipping points.

C. It’s time for a broader strategy to address the climate emergency and avoid climate catastrophe

- Addressing the near-term climate emergency requires selecting fast mitigation solutions that: provide the most avoided warming in the shortest period of time over the next decade or two;⁴⁷ slow the self-amplifying feedbacks and avoid or at least delay irreversible tipping points;⁴⁸ and protect the most vulnerable people and ecosystems from heat, drought, flooding, and other extremes⁴⁹ that will dramatically increase in severity and frequency with every increment of additional warming.⁵⁰
  - In addition to cutting CO₂ and super climate pollutants, other fast mitigation strategies must be employed, including protecting sinks.⁵¹ This combined approach is essential for achieving near-term and long-term climate targets.
- Limiting warming to 1.5 °C would prevent most of the tropics from exceeding the combined heat and humidity conditions beyond the survival limit.⁵² Warming of 2.7 °C by the end of the century would leave about 21% of the global population outside of the climate niche (2 to 2.5 billion people), while limiting warming to 1.5 °C would reduce this to about 4.4 to 4.8% (0.4 to 0.5 billion people).⁵³
• According to the IPCC, keeping the planet livable by limiting warming to 1.5 °C with no or limited overshoot requires reducing global human-caused CH4 emissions by 34% in 2030 and 44% in 2040 relative to modelled 2019 levels, in addition to cutting global CO2 emissions in half in 2030 and by 80% in 2040, with deep cuts to other SLCPs and N2O.54
  o AR6 WGIII further finds that “[d]eep GHG [greenhouse gas] 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 CO2 emissions that reverse warming in the latter half of the century…. Due to the short lifetime of CH4 in the atmosphere, projected deep reduction of CH4 emissions up until the time of net zero CO2 in modelled mitigation pathways effectively reduces peak global warming. (high confidence)”55
• These findings build on the conclusions of the IPCC’s Special Report on Global Warming of 1.5 °C that identified the three strategies that are essential for keeping the planet livable:
  i. reaching net zero CO2 by mid-century;
  ii. making deep cuts to super climate pollutants in the next decades; and
  iii. removing up to 1,000 billion tons of CO2 from the atmosphere by 2100.56

2. Feedbacks and tipping points are key to understanding planetary emergency

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.57 The IPCC defines a tipping point as “a critical threshold beyond which a system reorganizes, often abruptly and/or irreversibly.”58 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,59 as confirmed by two IPCC Special Reports.60 A recent assessment finds that exceeding 1.5 °C increases the likelihood of triggering or committing to six self-propagating climate tipping points (Figure 2).61
A. Climate models ignore or underestimate feedback and tipping point risks

Climate models either ignore or underestimate key feedbacks and tipping point risks. Domino-like interactions among these systems are projected to lower thresholds and increase the risk of triggering a global cascade of tipping points (Figure 3). Additional as-yet-undiscovered tipping points are possible due to limitations in current models and exclusion of processes such as those related to permafrost and other biogeochemical feedbacks. Self-amplifying feedbacks, including the loss of Arctic sea ice, are among the most vulnerable links in the chain of climate protection. Climate-driven changes in clouds act as another self-amplifying feedback leading to more warming and higher climate sensitivity. Above 1,200 ppm CO₂, a “stratocumulus cloud deck evaporation” tipping point could raise global warming levels by an additional 8 °C.

Extreme heat and other impacts unleashed by these feedbacks pose systemic risks to human and natural systems, including social, political, financial, and, ultimately, societal collapse. 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. 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. 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 reduced.
Figure 3. Climate tipping points

B. The Arctic may be the weakest link in safeguarding our climate

The Arctic is critical for climate stabilization, yet it may be the weakest link in the chain of climate protection. The Arctic’s sea ice provides a “great white shield” that reflects incoming solar radiation safely back to space. As the extent of the Arctic’s reflective sea ice continues to shrink, the amount of heat going into the darker ocean is increasing. This, in turn, causes more ice to melt in a self-amplifying feedback loop and makes sea ice loss unavoidable for decades to come. The Arctic air temperature is warming at a rate four times faster than the global average, and the last seven years (2016–2022) were the region’s seven warmest years on record. Half of the Arctic’s September sea ice is already gone, and the rest could disappear within 10 to 15 years. If all of the Arctic sea ice were lost for the sunlit months, it would add the warming equivalent of a trillion tons of CO₂, or 25 years of climate emissions at today’s rate. The Arctic’s land-based snow and ice is also melting and is expected to add a similar amount of warming. The intrusion of warmer ocean water from both the Atlantic and the Pacific is also contributing to Arctic warming and the melting of the sea ice, intensifying the impacts of late summer cyclones and further accelerating sea ice loss.

i. A rapidly warming Arctic

- Arctic air temperature is warming at a rate four times faster than the global average.
  - Arctic mean surface temperatures may rise by up to 10 °C above the 1985–2014 average, and in some regions up to 12 °C above the 1971–2000 average by the end of the century.
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). 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. 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, providing a refuge for the region’s ice-dependent flora and fauna.

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. During the warmer autumn season, the Northern Barents Sea area reached accelerated warming of up to 4.0 °C per decade between 2001–2020.

Only half of the summer Arctic sea ice in September remains, with the risk that September will be ice-free within 10 to 15 years. If all the Arctic sea ice were lost for the sunlit months, it would add the warming equivalent of a trillion tons of CO₂.

Arctic sea ice reaches its minimum extent or coverage every September. Between 1982–2022, the September minimum extent has decreased significantly, reducing at a rate of approximately 13% per decade. In addition to extent, the thickness and volume of Arctic sea ice have also decreased. During the September minimums of 1982–2020:

- Arctic sea ice extent decreased by 44% (from 7.6 million km² in 1982 to 4.3 million km² in 2020).
- Arctic sea ice thickness decreased by 48%.
- Arctic sea ice volume decreased by 72%.
- The 15 Septembers with the least Arctic sea ice extent have all been in the last 15 years; in September 2020, the Arctic sea ice reached the second lowest extent in the satellite record. September 2022 was the 9th lowest ice minimum on record, while September 2021 was the 12th lowest at the time, with one of the lowest recorded levels of multi-year ice.

The Arctic has lost 95% of its strong multi-year (>4 years old) Arctic sea ice, and is down to only 4.4% of the Arctic Ocean in March 2020; young, first-year ice—which is thinner, more fragile, and more susceptible to decline—now comprises about 70% of the ice pack.

Land-based snow and ice in the Arctic is also melting and is expected to add a similar amount of warming. 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.”

Polar ice volume is a strong indicator of changes in the planet’s fundamental climate state.
Between the periods of 1992–1999 and 2010–2019, the rate of glacier and ice sheet loss increased by a factor of four, and along with glacier mass loss, was the majority contributor to sea level rise between 2006–2018.\textsuperscript{105} A study that combined satellite observations with numerical models found that, between 1994 and 2017, glaciers and ice sheets lost 28 trillion tonnes of ice.\textsuperscript{106} (One trillion tonnes of ice is equivalent to a cube of ice taller than Mount Everest.\textsuperscript{107}) According to the study, “there can be little doubt that the vast majority of Earth’s ice loss is a direct consequence of climate warming.”\textsuperscript{108}

\textbf{Figure 4. Monthly sea ice extent anomalies Sep 1979–2022}

\textit{Source:} National Snow and Ice Data Center, \textit{Sea Ice Index}, \textquotedblleft Monthly Sea Ice Extent Anomaly Graph\textquotedblright\ (last visited 13 March 2023) (“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 2021 data. The anomaly data points are plotted as plus signs and the trend line is plotted with a dashed grey line.”).

\textbf{ii. Amplification of Arctic warming and sea ice loss—feedbacks and impacts}

- 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.”\textsuperscript{109}
  - Warmer oceans are also accelerating sea ice loss, with warmer Atlantic\textsuperscript{110} and Pacific\textsuperscript{111} 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”\textsuperscript{112} that is propagating northward. The strength of this warming is likely underestimated in CMIP6 models.\textsuperscript{113}
  - 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.\textsuperscript{114} Sea ice cover and ocean stratification in this region have been linked to abrupt changes during the last ice age.\textsuperscript{115}
  - With less sea ice in the Arctic Ocean, ocean waves can grow larger and accelerate ice breakup and retreat;\textsuperscript{116} late summer cyclones exacerbate this.\textsuperscript{117}
Exceptionally high winds in winter of 2020/21 drove multi-year ice into the Beaufort Sea, \textsuperscript{118} “where ice increasingly can’t survive the summer,” resulting in record loss of the Arctic’s multi-year ice. \textsuperscript{119}

Arctic warming also leads to a greater number of cyclones and to more intense cyclones, \textsuperscript{120} which further exacerbate Arctic sea ice decline and vice-versa. \textsuperscript{121}

\textbf{Figure 5. Late winter sea ice in the Arctic}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{image.png}
\caption{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).}
\end{figure}

\textbf{iii. We are perilously close to losing our Arctic climate control}

- The Arctic could become nearly sea ice-free in September as soon as the 2030s, further reducing its heat-reflecting ability. \textsuperscript{122}
  - 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. \textsuperscript{123}
  - 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. \textsuperscript{124}
  - The Barents Sea and Greenland Sea could become ice-free year-round by the end of the century under high emissions scenarios. \textsuperscript{125}
• In the extreme case when all Arctic sea ice is lost for the sunlit months, as could happen as early as mid-century, it would be the warming equivalent to one trillion tons of CO$_2$—on top of the forcing from the 2.4 trillion tons of CO$_2$ added in the 270 years since the Industrial Revolution, advancing warming by 25 years.
  o This additional warming would be the equivalent of adding 56 ppm of CO$_2$ to the current CO$_2$ concentration.
  o The added forcing in the Arctic would be 21 W/m$^2$; averaged globally this would equal 0.71 W/m$^2$ of global forcing, compared to the 2.16 W/m$^2$ added by anthropogenic emissions of CO$_2$ since the Industrial Revolution.
  o If all of 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.
• Additional factors contribute to further snow and ice loss in the Arctic.
  o Reduced Arctic snow cover is increasing the risk of wildfires, which emit black carbon, another super climate pollutant, while destroying sinks and emitting CO$_2$. Wildfires and permafrost thawing can “act together to expose and transfer permafrost C to the atmosphere very rapidly.” In 2021 alone, wildfires in the Arctic emitted 16 million metric tons of carbon.
  o The warming Arctic is also experiencing three times more lightning in the last decade, igniting more fires and threatening to accelerate permafrost thaw. Boreal fires which smolder in organic soils and remerge after months, called “zombie fires” or “overwintering fires,” emitted about 3.5 million metric tons of carbon between 2002 and 2018.
  o 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. From 2009–2018, shipping activity in the Norwegian Exclusive Economic Zone increased by 42%. Increased Arctic shipping lanes also introduce geopolitical problems and other evolving security risks.

C. Permafrost thaw feedback could rival major emitters for CO$_2$, CH$_4$, and N$_2$O

As the Arctic continues to warm at four times the global average, it is already starting to thaw the Arctic permafrost in a self-amplifying feedback loop that could release 110 to more than 550 Gt CO$_2$ this century, 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).

• Permafrost contains nearly twice the amount of carbon than is already in the atmosphere. As it thaws it releases ancient stores of CO$_2$, methane, and N$_2$O (which also destroys stratospheric ozone).
• Yet 82% of IPCC models do not include climate emissions from permafrost thaw.
• Arctic permafrost at high latitudes has warmed at a rate of 1 °C per decade since the 1980s. 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$_2$e (2.6 to 27) of methane, in addition to N$_2$O, which most estimates do not account for.\textsuperscript{149}

- In addition, up to 20% of the permafrost area accounting for half of permafrost carbon could experience abrupt local thaw events, such as the deep sinkholes observed in the Beaufort Sea.\textsuperscript{150}
  - These 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.\textsuperscript{151}
  - Models that consider only gradual thaw underestimate permafrost carbon emissions by 40% through 2300.\textsuperscript{152}
  - Some of the emissions from thawing permafrost are expected to be offset by the expanded growth of biomass, only if human emissions are curbed.\textsuperscript{153}

- 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.\textsuperscript{154}

- Wildfires are also increasing in the Arctic and this is accelerating permafrost thaw.\textsuperscript{155}
  - “Fire-induced permafrost thaw may be a dominant source of Arctic carbon emissions during the coming decades.”\textsuperscript{156}

- Thawing permafrost also impairs human settlements and health:
  - 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.\textsuperscript{157} Damage to Russian infrastructure alone due to permafrost thaw could cost US$ 69 billion by 2050.\textsuperscript{158}
  - Thousands of industrial sites in the Arctic risk mobilization of legacy contamination due to warming and thawing permafrost, which contain uncharacterized pathogens.\textsuperscript{159}

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

Another risk is that warming ocean waters will destabilize seabed methane hydrates.\textsuperscript{160} 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.\textsuperscript{161} 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.\textsuperscript{162} Although there is debate on the rate of potential release,\textsuperscript{163} the rate of methane release in the Chukchi Sea was higher in 2010s compared to 1990s.\textsuperscript{164} Release of land-based methane hydrates as glaciers recede could further amplify the permafrost feedback.\textsuperscript{165}

- 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.\textsuperscript{166} 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.”\textsuperscript{167}
• 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.\(^{168}\)

E. The approaching ice sheet tipping points

Several climate tipping points are at risk if warming exceeds 1.5 °C for more than several decades, with the Greenland Ice Sheet and West Antarctic Ice Sheet both already showing signs of approaching tipping thresholds estimated around 1.5–2 °C.\(^{169}\) Once triggered, significant ice loss is irreversible even with CO\(_2\) removal strategies.\(^{170}\) In 2021, Greenland reached record low levels of ice mass, with glaciers losing 31% more snow and ice per year than they did just 15 years ago.\(^{171}\) Antarctica sea ice extent reached a satellite-era record low in February 2022.\(^{172}\) The melting Greenland Ice Sheet is already the largest single contributor to the rate of global sea level rise,\(^{173}\) 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).\(^{174}\) Recent observations have shown 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.\(^{175}\) AR6 WGI was unable to exclude the possibility of sea level rise of up to 7.5 feet (2.3 meters) by 2100 due to uncertainties in ice sheet processes.\(^{176}\)

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

• Early warning signs suggest that the Greenland Ice Sheet is close to a tipping point.\(^{177}\) Currently, the best estimate of the threshold for irreversible melting of the Greenland Ice Sheet is around 1.6 °C (0.8–3.2 °C).\(^{178}\)
  o In the past two decades, the melt rate across Greenland increased 250–575%,\(^{179}\) and the ice discharge from the Greenland Ice Sheet substantially increased; this will likely persist in the coming years.\(^{180}\) On 28 July 2021, Greenland experienced a massive melt event that alone would be enough to cover the state of Florida by two inches of water.\(^{181}\)
  o If all of Greenland melted, it would contribute 5–7 meters of sea level rise; and while it may take thousands of years to see the full extent of the sea level rise, the “timescale of melt depends strongly on the magnitude and duration of the temperature overshoot.”\(^{182}\)
  o On 14 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).\(^{183}\)
• A new analysis calculated that 3.3% of the Greenland Ice Sheet (equivalent to 110 trillion tons of ice) will inevitably melt by the end of the century regardless of any climate emissions scenario, triggering at least 27.4 cm (10.8 in) of global sea level rise, and reaching as much as 78.2 cm (30.8 in).\(^{184}\)

ii. The Atlantic Meridional Overturning Circulation is weakening

• The melting of Greenland also contributes to the weakening of the Atlantic Meridional Overturning Circulation (AMOC), which has reached a critical “overturning” stage; the
observational data suggest that the AMOC has been weakening since 2008, “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.”

- 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. However, current models may be biased in favor of a stable AMOC.

- The collapse of AMOC can lead to faster sea level rise along parts of the Eastern United States and Europe, stronger hurricanes in the Southeastern United States, and reduced rainfall across the Sahel. If the sea level along U.S. coasts increased by 10–12 inches by 2050, the occurrence of destructive floods would increase five-fold. Such a collapse would shift weather patterns around the world, with potentially devastating consequences.

- In the southern hemisphere, meltwater from the Antarctic ice sheets can weaken the southern overturning circulation by 40% and the AMOC by 19% under a high-emission scenario by 2050, with climate impacts that could last for centuries.

### iii. The West Antarctic Ice Sheet is destabilizing

- In West Antarctica, losing the Thwaites glacier, which is currently the size of Florida or Britain, could raise sea levels by over two feet (65 cm). Once the Thwaites glacier retreats past a ridge 50 km upstream, the self-amplifying retreat of the glacier would “become unstoppable.”

- A new study warned that the Thwaites glacier has melted faster than previously observed and that a similar pace of rapid melt could occur in the future.

- The Thwaites glacier is already contributing to 4% of sea level rise. In the last 20 years, the glacier has lost more than 1,000 billion tons of ice and is continuing to lose ice at a rapidly increasing rate.

- One glaciologist found that the ice shelf buttressing the Thwaites glacier could collapse in as little as five years due to massive fractures caused by warmer ocean water that weakens the ice shelf, thereby setting off a “chain-reaction” that could eventually add 2 to 10 feet of sea level rise over centuries.

### F. The ocean is a heat battery

Compounding the risk from self-amplifying feedbacks and tipping points, warming will continue well after emissions stop; about 93% of the energy imbalance accumulates in the oceans as increased heat, which will return to the atmosphere on a timescale of decades to centuries after emissions stop. Between 2003–2018, the rate of ocean warming increased tenfold from 1958–1973 levels. The year 2022 saw the highest ocean heat content in historical records as the world’s oceans continue to warm. As noted 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).”

3. Cutting CO₂ 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 keeping temperatures below 1.5 °C by the end of this century. However, stopping burning fossil fuels, like coal and diesel, also means cutting co-emitted cooling aerosols. These cooling aerosols fall out of the atmosphere in days to months, which offsets reductions in warming from decarbonization until around 2050 and likely even accelerates warming over the first decade or more. As stated by climate scientist and IPCC author Joeri Rogelj: “The removal of air pollution, either through air quality measures or because combustion processes are phased out to get rid of CO₂, will result in an increase in the resulting rate of warming…. The only measures that can counteract this increased rate of warming over the next decades are methane reductions.”

• Air pollution that is co-emitted with CO₂ when sulfur-containing coal and oil are burned results in particles that reflect sunlight. These co-emitted sulfate “cooling aerosols” currently “mask” warming of about 0.5 °C; and while the accumulated CO₂ in the atmosphere will continue to cause warming for decades to centuries, the cooling aerosols fall out of the atmosphere within days to months once they are stopped at the source, unmasking more of the existing warming.

  o The temporary cooling effects of aerosols have been demonstrated in the past. The 1991 Mount Pinatubo eruption injected 15 million tons of sulfur dioxide (SO₂) into the atmosphere, temporarily cooling the planet by 0.5 °C for nearly two years.

  o Further evidence of the potential speed and magnitude of this unmasking effect is provided by the natural experiment of the pandemic shutdown, which abruptly reduced fossil fuel burning and resulted in temporary unmasking over South Asia that increased local radiative forcing by 1.4 Wm⁻², equivalent to three-fourths of radiative forcing from CO₂.

  o A recent assessment of satellites and other evidence finds that the net effect of anthropogenic aerosol forcing has changed from negative (cooling) to positive (warming) over the last two decades, contributing the equivalent of 15–50% of the increase in forcing due to CO₂ over the same time period, and concluding that “[t]his signal will most likely continue in the future, increasing the urgency for strong measures on reducing greenhouse gas emissions…”

• A previous study calculated that fast cuts to CO₂ could avoid 0.1 °C of warming by 2050 and up to 1.6 °C by 2100, not counting the extra warming from unmasking.

  o This would require CO₂ emissions to peak in 2030 and decline by 5.5% per year until carbon neutrality is reached around 2060–2070, after which emissions level off.

  o If CO₂ emissions were to peak in 2020 and decline at 5.5% per year until carbon neutrality is reached (around mid-century) then level off, this extreme scenario could avoid 0.3 °C of warming by 2050 and up to 1.9 °C by 2100, although unmasking of the cooling aerosol would still lead to net warming in the near term.
A separate study calculated near-term warming within the next two decades of 0.02–0.10 °C due to cuts to fossil fuel CO₂ emissions and associated reductions in cooling aerosols.²¹⁴

Figure 6. Temperature response of mitigation strategies focusing only on CO₂ (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-CO₂ 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): e2123536119.

4. Targeting short-lived super climate 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 also are known as “super climate pollutants.” AR6 WGI included a chapter on short-lived climate pollutants for the first time, which finds 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 CH₄ and BC mitigation would contribute to offsetting the additional
warming associated with \( \text{SO}_2 \) reductions that would accompany decarbonization *(high confidence).* The AR6 Synthesis Report further affirms 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)*”

- Cutting SLCPs is the only plausible way to limit warming due to unmasking of cooling aerosols over the next 20 years.
- Accounting for the co-emission of cooling aerosol from fossil fuel burning, a new study finds 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. In contrast, the dual strategy that simultaneously reduces the non-CO\(_2\) pollutants, especially the SLCPs, would result in net avoided warming by 2050 four times larger than the net effect of decarbonization alone would enable the world to stay well below the 2 °C limit, and significantly improve the chance of remaining below the 1.5 °C guardrail.
- In contrast to the limited amount of warming reduced at 2050 by cutting CO\(_2\) from fossil fuel emissions, fast cuts to SLCPs could avoid up to 0.6 °C of warming by 2050, and up to 1.2 °C by 2100, which would reduce projected warming in the Arctic by two-thirds, the rate of global warming by half, and avoid or at least delay self-amplifying feedbacks and tipping points.
  - AR6 WGIII finds that limiting warming to 1.5 °C with no or limited overshoot requires deep cuts to SLCPs, in particular reducing methane emissions by 34% in 2030 and 44% in 2040 relative to 2019 models and reductions of HFC emissions by 85% by 2050 relative to 2019. This re-affirms the conclusion by the IPCC’s *Special Report on Global Warming of 1.5 °C* that cutting SLCPs is essential for staying below 1.5 °C.
  - Similarly, the warning of the climate emergency issued in November 2019 from 11,000 scientists also emphasizes the importance of cutting SLCPs:
    - “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.”
  - In their 2021 update, the scientists stress the urgency of “massive-scale climate action” due to growing severity of impacts and risks from “the many reinforcing feedback loops and potential tipping points” and call for “immediate and drastic reductions in dangerous short-lived greenhouse gases, especially methane.”
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.\textsuperscript{226} 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\textsubscript{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.\textsuperscript{227} While the UNFCCC currently requires using the GWP\textsubscript{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\textsubscript{20} or absolute temperature potentials.\textsuperscript{228} Indeed, using GWP\textsubscript{100} alone systematically underestimates the importance of methane emissions and “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.”\textsuperscript{229}

AR6 has updated the metrics for methane as follows: GWP\textsubscript{20} is 81.2 and GWP\textsubscript{100} is 27.9.\textsuperscript{230} Table 1 below summarizes GWP values for methane from IPCC reports.

<table>
<thead>
<tr>
<th></th>
<th>Methane (CH\textsubscript{4})</th>
<th>AR6</th>
<th>AR5</th>
<th>AR4</th>
<th>TAR</th>
<th>SAR</th>
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<tbody>
<tr>
<td>GWP\textsubscript{20}</td>
<td>81.2</td>
<td>84</td>
<td>86*</td>
<td>72</td>
<td>62</td>
<td>56</td>
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<tr>
<td>GWP\textsubscript{100}</td>
<td>27.9</td>
<td>28</td>
<td>34*</td>
<td>25</td>
<td>23</td>
<td>21</td>
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<tr>
<td>Fossil CH\textsubscript{4}</td>
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<td></td>
<td></td>
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<tr>
<td>GWP\textsubscript{20}</td>
<td>82.5 ± 25.8</td>
<td>85</td>
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</tr>
<tr>
<td>GWP\textsubscript{100}</td>
<td>29.8 ± 11</td>
<td>30</td>
<td>--</td>
<td>--</td>
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<tr>
<td>Non-fossil CH\textsubscript{4}</td>
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</tr>
<tr>
<td>GWP\textsubscript{20}</td>
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<tr>
<td>GWP\textsubscript{100}</td>
<td>27.2 ± 11</td>
<td>--</td>
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</table>

* 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\textsubscript{2}. Metrics such as CO\textsubscript{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\textsubscript{2} emissions.\textsuperscript{231} 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.\textsuperscript{232} 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.\textsuperscript{233}

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 tonnes of methane (MtCH\textsubscript{4}), and temperature impacts rather than GWP metrics where possible.
A. Methane (CH₄)

According to AR6 WG1, methane pollution has already caused 0.51 °C of warming of the total observed warming for 2019 of 1.06 °C (0.88–1.21 °C).²³⁴ Warming caused by methane will continue to increase as anthropogenic methane emissions, which are responsible for nearly 45% of current net warming,²³⁵ continue to increase. Recent studies have also identified feedback mechanisms from natural sources and sinks, which accelerated the growth of methane in 2020 and 2021, including increased emissions from wetlands and reduced capacity of the atmosphere to remove methane.²³⁶ 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 hydroxy radical.²³⁷

As noted by the U.S. White House, “Methane is a potent greenhouse gas and, according to the latest IPCC report, accounts for about half of the 1.0 degree Celsius net rise in global average temperature since the pre-industrial era.”²³⁸ More leaders are starting to recognize the importance of methane, including former U.S. President Barack Obama, who declared at the 26th Conference of the Parties (COP26) that “curbing methane emissions is currently the single fastest and most effective way to limit warming.”²³⁹

Global Methane Assessment

- Cutting methane emissions is the biggest and fastest strategy for slowing warming and keeping 1.5 °C within reach.²⁴⁰ A 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 and avoid nearly 0.3 °C of warming by the 2040s.²⁴¹
  - This would prevent 255,000 premature deaths (not including additional benefits of preventing approximately 200,000 premature ozone-related deaths), 775,000 asthma-related hospital visits, 73 billion hours of lost labour from extreme heat, and 26 million tonnes of crop losses globally (annual value beginning in 2030)).²⁴² Each tonne of methane reduced generates US $4,300 in health, productivity, and other benefits.²⁴³ 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 tonne of CO₂e for GWP₁₀₀ and US $7 per tonne of CO₂e for GWP₂₀), 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, costing less than 3% of net income from oil and gas in 2022.²⁴⁴
- 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.”²⁴⁵
Table 2. Methane mitigation potential in 2030 by sector in MtCH₄/yr and Mt/yr of CO₂e

<table>
<thead>
<tr>
<th></th>
<th>Mt CH₄/yr</th>
<th>Mt CO₂e/yr [GWP₁₀₀]</th>
<th>Mt CO₂e/yr [GWP₂₀]</th>
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<tbody>
<tr>
<td>Oil &amp; gas</td>
<td>29–57</td>
<td>812–1,596</td>
<td>2,436–4,788</td>
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<tr>
<td>Waste</td>
<td>29–36</td>
<td>812–1,008</td>
<td>2,436–3,024</td>
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<tr>
<td>Agriculture</td>
<td>10–51</td>
<td>280–1,428</td>
<td>2,840–4,284</td>
</tr>
<tr>
<td>Coal</td>
<td>12–25</td>
<td>336–700</td>
<td>1,008–2,100</td>
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</table>


- Fast action to pursue all available methane mitigation measures now could slow the global rate of warming by 30% by mid-century. This is consistent with the 2011 UNEP/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.
  - 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.
  - Rapid reductions in methane emissions also reduces the risk of losing all of the reflective summer Arctic sea ice.
- 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.
  - 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. 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.

Figure 7. Methane reductions compared to global mean surface temperature responses to changes in fossil-fuel-related emissions (CO₂ + SO₂)

Mitigation and Removal

- Anthropogenic emissions, which make up 60% of total global methane emissions,\(^{253}\) come primarily from three sectors: energy production (~35%), agriculture (~40%), and waste (~20%).\(^{254}\) Currently available mitigation measures could reduce emissions from these major sectors by about 180 million metric tonnes of methane per year (MtCH\(_4/yr\)), approximately 45%, by 2030.\(^{255}\)

- 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;\(^{256}\)
  - Reducing leaks\(^{257}\) and venting\(^{258}\) in the oil and gas sector. The Clean Air Task Force states that prohibiting venting of natural gas can reduce emissions by 95%;\(^{259}\)
  - Eliminating flaring from oil and gas operations, while shifting to clean energy.\(^{260}\)
  - 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%;\(^{261}\)
  - Eliminating gas in new construction and phasing out leaky gas stoves;\(^{262}\)
  - Upgrading solid waste and wastewater treatment;\(^{263}\) 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.\(^{264}\)

- There is research underway on the best approach for removing atmospheric methane.\(^{265}\) This is especially important, as 35–50% of methane emissions are from natural sources.\(^{266}\)

Methane removal is discussed further in Section 5C.

  - A modelling study by a Stanford University-led team calculates that removing around three years’ worth of human-caused methane 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 (0.075 °C for methane compared to 0.02 °C for CO\(_2\)).\(^{267}\)
  - The nonprofit Methane Action has stated that removing methane in conjunction with methane emissions reductions can trim an estimated 0.4–0.6 °C of warming.\(^{268}\)

Global Methane Pledge

- The Global Methane Pledge was formally launched at the high-level segment of COP26 on 2 November 2021.\(^{269}\) Initially announced by the United States and the European Union at the Major Economies Forum on Energy and Climate hosted by President Biden on 17 September 2021,\(^{270}\) the voluntary Pledge commits governments to a collective goal of reducing global methane emissions by at least 30% below 2020 levels by 2030 and moving towards using the highest-tier IPCC good practice inventory methodologies to quantify methane emissions, with a particular focus on high emission sources. As of February 2023, 150 countries including the EU have joined the Pledge,\(^{271}\) representing approximately 70% of the global economy and nearly half of anthropogenic emissions.\(^{272}\) At least 20 global philanthropic organizations pledged $328 million to support methane reduction efforts.\(^{273}\)
  - Successful implementation of the Pledge would reduce warming by at least 0.2 °C by 2050,\(^{274}\) and would keep the planet on a pathway consistent with staying within
1.5 °C. This reduction is roughly equivalent to a reduction of 35% below projected 2030 levels. Deploying all available and additional measures, as described in the GMA, could lead to a 45% reduction below 2030 levels to achieve nearly 0.3 °C in avoided warming by the 2040s.

Further, implementing the Pledge would provide additional benefits, including prevention of approximately 200,000 premature ozone-related deaths, avoidance of ~580 million tons of yield losses of staple crops like rice and maize annually, avoidance of ~US$ 500 billion per year in losses due to non-mortality health impacts, and impacts on forestry and agriculture, and avoidance of ~1,600 billion hours of work lost per year due to heat exposure. Nearly 85% of targeted measures have benefits that outweigh the net costs.

In June 2022, the U.S., EU, and 11 other countries launched the Global Methane Pledge Energy Pathway, which includes US$ 59 million in funding to support methane reductions in the oil and gas sector. The funding includes $4 million to support the World Bank Global Gas Flaring Reduction Partnership, US$ 5.5 million to support the Global Methane Initiative, up to US$ 9.5 million from the UNEP International Methane Emissions Observatory to support scientific assessments of methane emissions and mitigation potential, and up to US$ 40 million annually from the philanthropic Global Methane Hub to support methane mitigation in the fossil energy sector.

In August 2022, the Inflation Reduction Act was signed into law, allocating US$ 369 billion for climate and clean energy policies, including about US$ 20 billion in incentives to reduce greenhouse gas emissions including methane from the agriculture sector and US$ 1.5 billion in support for reducing methane emissions from the oil and gas sector through the Methane Emissions Reduction Program and a fee on methane leaks. This Act is estimated to reduce U.S. GHG emissions by 40% below 2005 levels by 2030.

In November 2022, the U.S. and EU launched the Pledge’s Food and Agriculture Pathway and Waste Pathway to advance methane mitigation in the agriculture and waste sectors. The Food and Agriculture Pathway will leverage up to US$ 400 million to help smallholder farmers transition dairy systems to lower emission, climate-resilient pathways and raise US$ 70 million for a new Enteric Methane Research and Development Accelerator.

IGSD’s (2022) 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 urgent; 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 (O₃)**

Tropospheric ozone is a local air pollutant and significant GHG. Ozone is not directly emitted but is a product of atmospheric reactions with precursor pollutants, notably methane and other volatile organic compounds and nitrogen oxides (NOₓ). In addition to contributing to warming, it is responsible for millions of premature deaths, billions of dollars’ worth of crop losses annually, and weakening of carbon sinks.
Mitigation

- Reducing methane has the added effect of reducing tropospheric ozone levels. A recent study estimated methane’s contribution to the present-day tropospheric ozone burden at 35%. Methane is likely to play a greater role in tropospheric ozone formation as emissions of other precursors decrease due to air pollution controls.
  - Through tropospheric ozone, methane could be added to the 1999 Protocol to Abate Acidification, Eutrophication, and Ground-Level Ozone (Gothenburg Protocol) to the UNECE Convention on Long-Range Transboundary Air Pollution (LRTAP). LRTAP is a regional treaty framework between Europe, North America, Russia, and former Eastern Bloc countries for reducing transboundary air pollution and understanding related science. Methane is the last remaining major ozone precursor not explicitly controlled under the Gothenburg Protocol as currently amended.
  - Stopping methane leaks from oil and gas also reduces non-methane ozone precursors and contributes to improving local air quality.

- As a local air pollutant, tropospheric ozone (and black carbon, discussed in the next section) can be addressed under national or regional air pollution laws.

C. Black carbon

Black carbon and tropospheric ozone are local air pollutants and are typically addressed under national or regional air pollution laws, as well as through the voluntary programs of the CCAC. Black carbon is not a 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, as well as biofuels and biomass. Fossil fuel combustion is the largest source of air pollution particles and tropospheric ozone, which kills about 8–10 million people per year. Cutting black carbon and tropospheric ozone can save up to 2.4 million lives every year and increase annual crop production by more than 50 million tons, worth US$4–33 billion a year, as calculated in 2011.

Mitigation

- It is possible to reduce 70% of global black carbon emissions by 2030, including by implementing the following measures:
  - Ensuring fast ratification of the Gothenburg Protocol and the 2012 amendment that includes controls for black carbon;
  - Reducing on-road and off-road diesel emissions by mandating diesel particulate filters while eliminating diesel and other high-emitting vehicles and shifting to clean forms of transportation;
  - Eliminating flaring, while shifting to clean energy;
  - Switching to clean cooking and heating methods; 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).
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) has successfully phased out the production and use of ozone-depleting and potent climate pollutants chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), preventing GHG emissions that otherwise could have equalled or exceeded the emissions of CO$_2$ in 2010.$^{304}$ Avoided warming from the Montreal Protocol is delaying the first appearance of ice-free Arctic summer by up to 15 years.$^{305}$
  - By end of the century, the Montreal Protocol’s steady progress over its 33 years of operation will avoid up to 2.5 °C of warming that otherwise would have already pushed the planet past irreversible tipping points.$^{306}$ 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.
  - This is in addition to achieving its original objective of putting the stratospheric ozone layer on the road to full recovery by 2066.$^{307}$
  - Emissions of these ozone depleting super-climate pollutants between 1955 and 2005, were 20% more effective at warming than CO$_2$, accounted for 37% of anthropogenic Arctic warming, and a third of the loss in September sea ice extent due to anthropogenic emissions.$^{308}$
  - Narrowing exemptions for CFCs and HCFCs used as feedstocks (in plastics, for example) and produced as by-products could further ensure these benefits.$^{309}$
- 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.$^{310}$

- 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.$^{311}$
  - The initial phasedown schedule of the Kigali Amendment would lock in reductions limiting warming from HFCs in 2100 to about 0.04 °C, avoiding about 90% of the potential, or up to 0.44 °C.$^{312}$
  - Accelerating the phasedown could reduce HFC emissions by an additional 72% in 2050, increasing the chances of staying below 1.5 °C this century.$^{313}$
  - More mitigation is available from a faster phasedown schedule; collecting and destroying HFCs at end-of-product life; recycling and destroying HFC “banks” embedded in products and equipment; early replacement of older inefficient cooling equipment using HFC refrigerants; and reducing refrigerant leaks through better design, manufacturing, and servicing.$^{314}$
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 Gt CO₂e of emissions by the end of the century. 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.

Improving energy efficiency of cooling equipment during the HFC phasedown can more than double the climate benefits in CO₂e by reducing emissions from the power plants that provide the electricity to run the equipment. As of June 2023, 150 countries have accepted, ratified, or approved the Kigali Amendment, including China and India.

The U.S. is implementing the Kigali phasedown schedule through the American Innovation and Manufacturing (AIM) Act signed into law in December 2020. The AIM Act and related implementing regulations will reduce the production and consumption of HFCs by 85% by 2036. Twelve states have instituted HFC prohibitions for products and equipment where low-GWP alternatives are available, and six more proposed HFC bans. On 21 September 2022, the U.S. Senate approved ratification of the Kigali Amendment.

E. Nitrous oxide (N₂O)

While not an SLCP, N₂O is a potent greenhouse gas (GHG) and the most significant anthropogenic ozone-depleting substance (ODS) not yet controlled by the Montreal Protocol. Its global warming potential over 100 years (GWP₁₀₀) is 273 times greater than total CO₂. Through mandatory control measures, the Montreal Protocol could spur adoption of technologies to reduce N₂O emissions, which are contributing the equivalent of about 10% of today’s CO₂ warming. In its 2022 Quadrennial Assessment Report, Montreal Protocol's Scientific Assessment Panel (SAP) states that N₂O emissions accelerated over the last 20 years and now exceeded the highest projections. The anthropogenic N₂O emissions in 2020 were more than 20% the ozone depleting potential of peak CFC emissions in 1987.

Mitigation

- Controlling N₂O emissions could provide climate mitigation of about 1.67 Gt CO₂e GWP₁₀₀ by 2050 with 0.94 Gt CO₂e from agriculture and about 0.6 Gt CO₂e from industry in 2050.
- Under current policies and programs, N₂O emissions are projected to rise by 8% from 2021-2030. If net zero emissions are reached by 2100, emissions fall by 2%, with a 30% decrease in energy-related emissions.
- Reducing N₂O emissions to levels compliant with the 1.5°C Paris Agreement guardrail will increase stratospheric ozone at levels equivalent to one quarter the impact of eliminating all emissions from controlled ODSs starting in 2023, averaged over 2020–2070. Such reductions will also reduce radiative forcing by 0.04 W m⁻² averaged over 2023–2100, more than half the decrease in radiative forcing resulting from eliminating all HFCs.
- Full recovery of the ozone layer will be delayed if N₂O emissions continue to increase.
The agriculture, forestry, and land use sector (AFOLU) accounted for 82% of global anthropogenic N$_2$O emissions, contributing approximately 1.8 GtCO$_2$e/yr between 2010 and 2019.\textsuperscript{334}

In the agriculture sector, several solutions have been found to be cost-effective in reducing N$_2$O emissions from agricultural processes, including precision farming using variable rate technology and nitrogen inhibitors that suppress the microbial activity that produces N$_2$O. Studies have found that variable rate technology can increase yields by 1–10% while reducing 4–37% of nitrogen fertilization.\textsuperscript{335} Moreover, allowing a continued increase in N$_2$O emissions while reducing CO$_2$ and CH$_4$ emissions could reverse progress on recovery of the stratospheric ozone layer.\textsuperscript{336} o Adapting solutions for smallholder farmers in the Global South requires additional attention.\textsuperscript{337} o Another solution, the SOP LAGOON product line,\textsuperscript{338} stimulates nitrogen uptake in crops and inhibits GHG emissions from manure.\textsuperscript{339}

For industry, most emissions are produced in the manufacture of nitric and adipic acids for a variety of uses. Proven abatement technology at nitric and adipic acid production facilities could reduce 86% of projected industrial N$_2$O emissions by 2030.\textsuperscript{340} o In the industrial sector, abatement technology has been available and utilized by manufacturers in developed countries since the 1990s.\textsuperscript{341} Moreover, only a few countries produce 86% of industrial N$_2$O: China, the United States, Egypt, and Russia.\textsuperscript{342} o Out of the 39 adipic acid plants, one plant is in the U.S. and 11 plants in China operate without or with significantly lower pollution control technology than the industry standard abatement levels of 98%.\textsuperscript{343}

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

A. Protecting the Arctic albedo and permafrost

Rapid reductions in super climate pollutants are key to protecting the Arctic. The \textit{Global Methane Assessment} calculated that strategies to cut methane emissions by 40–45% by 2030 could avoid nearly 0.3 °C by the 2040s, and 0.5 °C in the Arctic by 2050, 60% more than the global average.\textsuperscript{344} 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.\textsuperscript{345}

- The Arctic is nearly five times more sensitive to black carbon emitted in the Arctic region than from similar emissions in the mid-latitudes.\textsuperscript{346} 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.\textsuperscript{347} o Heavy-Fuel Oil (HFO) used in shipping is a significant source of black carbon and sulfates.\textsuperscript{348} The International Maritime Organization (IMO) will ban HFO use in the Arctic beginning in July 2024 for some ships, with waivers and exemptions for others until July 2029.\textsuperscript{349} (HFO has been banned in the Antarctic since 2011.\textsuperscript{350}) o 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.\textsuperscript{351} However, if the Arctic HFO ban were imposed without the waivers or exemptions, black carbon emissions could have been reduced by 30\%\textsuperscript{352}

- In 2019, Arctic Council countries set a collective target of reducing black carbon emissions by 25–33\% by 2025 compared to 2013 levels.\textsuperscript{353} Adopting best available techniques could halve black carbon emissions by 2025 and surpass the current goal.\textsuperscript{354} 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.\textsuperscript{355}

- 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.\textsuperscript{356}

- 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.\textsuperscript{357} Insurance companies are also starting to commit to banning coverage of Arctic oil projects, including AXA, Swiss RE, and Zurich Insurance.\textsuperscript{358}

- For Arctic ice management, additional strategies being investigated for protecting and restoring Arctic ice include enhancing albedo of Arctic sea ice and thickening sea ice.\textsuperscript{359}

### B. Protecting forests and other sinks

Deforestation combined with global warming risks enhancing warming feedbacks and crossing ecosystem tipping points, such as loss of the Amazon and Boreal forest.\textsuperscript{360} Halting the destruction of our forests and other carbon sinks so they continue to store carbon and do not turn into sources of \( \text{CO}_2 \) can provide fast mitigation, while also protecting biodiversity.\textsuperscript{361} Forest bioenergy is not a climate solution.\textsuperscript{362}

- Under current warming trends, the global land sink, which now mitigates \~30\% of carbon emissions and has avoided 0.4 \( \text{o} \text{C} \) since 1900,\textsuperscript{363} could be cut by half as early as 2040, as increasing temperatures reduce photosynthesis and speed up respiration,\textsuperscript{364} calling into question national pledges under the Paris Accord, which rely heavily on land uptake of carbon to meet mitigation goals.\textsuperscript{365}

- 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 Gt\( \text{CO}_2 \)] by 2100.\textsuperscript{366} If all of the carbon (10 years’ worth of human emissions) stored in the Amazon were released, the planet could warm by 0.3 \( \text{o} \text{C} \).\textsuperscript{367} 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.\textsuperscript{368}
  - 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 \( \text{o} \text{C} \) warmer than intact forests. \( \text{CO}_2 \) 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.\textsuperscript{369}

- Accelerated warming in the boreal zones has intensified wildfires\textsuperscript{370} and pest-outbreaks,\textsuperscript{371} leading to large-scale tree mortality events. Such events have been both abrupt and irreversible, as intermediate stages of boreal forest regeneration are proving unstable.\textsuperscript{372} 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.\textsuperscript{373} While boreal forest range shifts have high potential to propel self-amplifying feedbacks, the net warming impact remains uncertain.\textsuperscript{374}

- The Amazon forest is already within the bounds of its estimated tipping point, 20-40% of complete loss\textsuperscript{375} with 20% destroyed completely and an additional 6% beyond repair absent human intervention.\textsuperscript{376}
  - Continued deforestation and drying in the Amazon under high-emissions scenarios could result in up to a 50% loss in forest cover by 2050.\textsuperscript{377}
  - Changes to the global water cycle may be pushing the Amazon to a tipping point.\textsuperscript{378} The combination of drier conditions, deforestation, and warming have been reducing Amazon forest resilience since 2000, increasing the risk of dieback.\textsuperscript{379}
  - 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,\textsuperscript{380} 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.\textsuperscript{381}

- Conservation International estimates that Earth’s ecosystems contain 139 billion metric tons (Gt C) [510 GtCO\textsubscript{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\textsubscript{2}], the Congo Basin (8.1 Gt C) [29.7 GtCO\textsubscript{2}], and New Guinea (7.3 Gt C) [26.8 GtCO\textsubscript{2}], with additional reserves in boreal forests, mangroves, and peatlands.\textsuperscript{382}

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\textsubscript{2}O and sequester carbon.\textsuperscript{383}

- Effective ways to protect forests, peatlands, and other sinks include:
  - Promoting forest protection and proforestation to allow existing forests to achieve their full ecological potential;\textsuperscript{384}
  - Preserving existing peatlands and restoring degraded peatlands;\textsuperscript{385}
  - Restoring coastal “blue carbon” ecosystems;\textsuperscript{386} and
  - Prohibiting bioenergy.\textsuperscript{387}
- Global government-led efforts to protect forests are increasing.
At COP26, world leaders agreed to halt deforestation by 2030 in the **Glasgow Leaders’ Declaration on Forests and Land Use**. As of February 2023, 145 countries have committed to this agreement, including Brazil, China, Russia, and the United States, covering about 91% of the world’s forests. This declaration includes US$12 billion in funding for forest-related climate finance between 2021–2025, an additional US$7 billion in funding from private companies, and a global roadmap to make 75% of forest commodity supply chains sustainable.

The U.S. launched a parallel domestic **Plan to Conserve Global Forests: Critical Carbon Sinks**. This is an “all-of-government effort” to end natural forest loss, preserve global ecosystems, including carbon sinks, and restore at least an additional 200 million hectares of forests and other ecosystems by 2030, with a dedicated fund of US$9 billion to support this effort.

### C. Removing super pollutants from the atmosphere

Scientists and funders are developing a research agenda for removing methane and other non-CO\textsubscript{2} greenhouse gases from the atmosphere. Pathways under consideration to remove methane from the atmosphere include catalytic oxidation, microbial filters, and augmentation of natural sinks. Catalytic systems are likely to involve technology already being developed for application to environments with heightened methane concentrations, such as coal mines and dairy barns. Additionally, other climate interventions have started looking further into monitoring methane and other GHG emissions to determine the best roadmap for research.

- The U.S. government has started to explore options to remove methane from the atmosphere.
  - In April 2021, the Department of Energy’s Advanced Research Projects Agency-Energy (ARPA-E) announced a US$35 million program to reduce methane emissions, called REMEDY (Reducing Emissions of Methane Every Day of the Year). This three-year research program looks to reduce methane emissions from the oil, gas, and coal sectors. According to ARPA-E, these three sources contribute to at least 10% of U.S. anthropogenic methane emissions. In developing the REMEDY program, ARPA-E recognized the need for further research on methane capture from the air in parallel with efforts to capture CO\textsubscript{2}.
  - In July 2022, ARPA-E’s budget was doubled by the Creating Helpful Incentives to Produce Semiconductors (CHIPS) and Science Act.
- Other methane removal interventions might target natural methane sources.
  - One company is testing the possibility of installing passive systems to capture and flare methane bubbling from Arctic lakes.
  - Other pathways, such as the augmentation of natural sinks could also develop into viable strategies.
- These methane and non-CO\textsubscript{2} removal efforts could complement carbon removal projects in the U.S., Europe, and elsewhere.
IGSD’s (2022) Background Note on Methane Removal provides further information on proposed and active research efforts.

6. Conclusion

Global warming is projected to cross the 1.5 °C guardrail as soon as the early 2030s. Policies that rely on decarbonization alone are insufficient to slow the near-term warming to keep the planet even 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 carbon dioxide (CO₂) and other largely neglected 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.⁴⁰³

Combining efforts to cut CO₂ emissions by decarbonizing the energy system with mitigation measures targeting non-CO₂ 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 from 2030 to 2050, which would slow the rate of warming a decade or two earlier than decarbonization alone making it possible for the world to stay below the 1.5 °C guardrail⁴⁰⁴ and avoid triggering a cascade of tipping points.⁴⁰⁵ 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 net zero by 2050 to stabilize temperatures in the longer term.⁴⁰⁶

AR6 is a “code red” for the climate emergency.⁴⁰⁷ The IPCC’s 2018 Special Report on 1.5 °C presented the three essential strategies for keeping the planet relatively safe: reducing CO₂, reducing super climate pollutants, and removing up to 1 trillion tons of CO₂ from the atmosphere by 2100.⁴⁰⁸ Cutting super climate pollutants is the only known strategy that can slow warming and feedbacks in time to avoid catastrophic and perhaps existential impacts⁴⁰⁹ from Hothouse Earth,⁴¹⁰ other than perhaps solar radiation management, which carries its own risks and governance challenges.⁴¹¹

In 2021, more leaders and policymakers recognized the importance and potential of targeting super climate pollutants than ever before. A new climate architecture is starting to emerge, as demonstrated in the realignment of goals of the delayed COP26 in 2021 compared to the goals announced in 2020:

“Four shifts in focus reflect this new architecture; first, the near-unanimous recognition of the impending climate emergency and the need to limit warming to 1.5 degrees Celsius; second, the recognition “that 2030 is the new 2050,” as French President Emmanuel Macron said, and that major emission cuts have to be made in this decade (note also that the U.S.-China Joint Glasgow Declaration marked the first time that the United States and China acknowledged the urgency of climate action in this “critical decade” of the 2020s); third, the recognition that cutting non-CO₂ emissions (particularly methane) is essential for slowing warming in the next couple of decades and that cuts to CO₂ alone cannot address the near-term emergency; and fourth, the addition of sector-specific approaches in recognition that it is often more efficient and effective to address individual sectors of the economy in reaching climate solutions.”⁴¹²
References

1 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 N₂O, slows the rate of warming a decade or two earlier than decarbonization alone and avoids the 2°C threshold altogether. These non-CO₂ 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 CO₂ 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 CH₄, BC, HFC, and N₂O (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-CO₂ measures is 0.26°C, almost 4 times larger than the net benefit of decarbonization alone (0.07°C) (Table S5)."). See also 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 CO₂ 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 CO₂ 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).").

2 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 CO₂ emissions, as for the CO₂-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 °C (range 0.2 to 1.3 °C) at 2040. This is a large portion of the 1.1 °C (range 0.7 to 1.7 °C) 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 CH₄ plus BC measures was −0.54 ± 0.05°C in the climate model. ...Roughly half the forcing is relatively evenly distributed (from the CH₄ 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., Kieendl-Scharr A., Kliment Z., Xiao C., & 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 CH₄, 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).”).

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 adaptive capacity. There are limits to adaptation and hence adaptation has to be integrated with mitigation actions to avoid crossing the limits.”); where 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).”).

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).”).

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).”).
6 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. 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. 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.”). See also Hansen J. E., Sato M., Simons L., Nazarenko L. S., Sangha L., von Schuckmann K., Loeb N. G., Osman M. B., Jin Q., Kharecha P., Tsélidou G., Jeong E., Lacis A., Ruedy R., Russell G., Cao J., & Li J. (23 May 2023) *Global warming in the pipeline*, IzV. Atmos. Ocean. Phys. (preprint): 1–62, 39 (“With current policies, we expect climate forcing for a few decades post-2010 to increase 0.5–0.6 W/m² 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. 25).” Figure 25 caption reads “Edges of the predicted post-2010 accelerated warming rate (see text) are 0.36 and 0.27°C per decade.”).

7 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.), 6 (“Global surface temperature was around 1.1°C above 1850–1900 in 2011–2020 (1.09°C [0.95°C–1.20°C])², with larger increases over land (1.59 [1.34 to 1.83°C]) than over the ocean (0.88°C [0.68°C–1.01°C])⁸. Observed warming is human-caused, with warming from greenhouse gases (GHG), dominated by CO₂ and methane (CH₄), partly masked by aerosol cooling (Figure 2.1).”).

8 National Oceanic and Atmospheric Administration National Centers for Environmental Information (2023) *Assessing the Global Climate in 2022* (last visited 11 June 2023) (“Global land and ocean surface temperature: The 2022 average temperature across global surfaces was 1.55°F (0.86°C) above the 20th-century average of 57.0°F (13.9°C) – the sixth highest among all years in the 1880-2022 record. This was also the 46th-consecutive year (since 1977) with global temperatures, at least nominally, above the 20th-century average. The 10-warmest years on record have all occurred since 2010, with the last nine years (2014-2022) among the 10-warmest years.”).

9 See Copernicus Climate Services (9 January 2023) *2022 was a year of climate extremes, with record high temperatures and rising concentrations of greenhouse gases* (last visited 11 June 2023) (“2022 was the 5th warmest year – however, the 4th-8th warmest years are very close together. The last eight years have been the eight warmest on record. The annual average temperature was 0.3°C above the reference period of 1991-2020, which equates to approximately 1.2°C higher than the period 1850-1900. Atmospheric carbon dioxide concentrations increased by approximately 2.1 ppm, similar to the rates of recent years. Methane concentrations in the atmosphere increased by close to 12 ppb, higher than average, but below the last two years’ record highs. La Niña conditions persisted during much of the year, for the third year in a row”); National Aeronautics and Space Administration (12 January 2023) *NASA Says 2022 Fifth Warmest Year on Record, Warming Trend Continues*; and National Oceanic and Atmospheric Administration (12 January 2022) *2022 was world’s 6th-warmest year on record*. 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.”).

10 National Oceanic and Atmospheric Administration National Centers for Environmental Information (2022) *September 2022 Global Climate Report* (“The January–September global surface temperature was 0.86°C (1.55°F) above the 1901-2000 average of 14.1°C (57.5°F) — the sixth-highest January–September temperature in the 143-year...
Currently 2%, or “the year 2022 is very likely to rank among the ten warmest years on record but a less than 5% chance to rank among the five warmest years on record.”). 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 ("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. 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 0.1°C 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 °C, but this increase does not represent additional physical warming since the AR5.”).

11 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 Xu Y., Ramanathan V., & Victor D. G. (2018) Global warming will happen faster than we think, Comment, NATURE 564(7734): 30–32, 30–31 ("But the latest IPCC special report underplays another alarming fact: global warming is accelerating. Three trends—rising emissions, declining air pollution and natural climate cycles—will combine over the next 20 years to make climate change faster and more furious than anticipated. In our view, there’s a good chance that we could breach the 1.5 °C level by 2030, not by 2040 as projected in the special report (see ‘Accelerated warming’). The climate-modelling community has not grappled enough with the rapid changes that policymakers care most about, preferring to focus on longer-term trends and equilibria."). Since Xu, Ramanathan, and Victor comment was published, the IPCC has updated its estimate for when 1.5 °C will be exceeded: see 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 Dvorak M. T., Armour K. C., Frierson D. M. W., Proistosescu C., Baker M. B., & Smith C. J. (2022) Estimating the timing of geophysical commitment to 1.5 and 2.0 °C of global warming, NAT. CLIM. CHANGE 12: 547–552, 547 ("Following abrupt cessation of anthropogenic emissions, decreases in short-lived aerosols would lead to a warming peak within a decade, followed by slow cooling as GHG concentrations decline. This implies a geophysical commitment to temporarily crossing warming levels before reaching them. Here we use an emissions-based climate model (FaIR) to estimate temperature change following cessation of emissions in 2021 and in every year thereafter until 2080 following eight Shared Socioeconomic Pathways (SSPs). Assuming a medium-emissions trajectory (SSP2–4.5), we find that we are already committed to peak warming greater than 1.5 °C with 42% probability, increasing to 66% by 2029 (340 GtCO2 relative to 2021). Probability of peak warming greater than 2.0 °C is currently 2%, increasing to 66% by 2057 (1,550 GtCO2 relative to 2021). Because climate will cool from peak warming as GHG concentrations decline, committed warming of 1.5°C in 2100 will not occur with at least 66% probability until 2085."); and Hansen J. E., Sato M., Simons L., Nazarenko L. S., Sangha I., von Schuckmann K., Loeb N. G., Osman M. B., Jin Q., Kharecha P., Tselioudis G., Jeong E., Lacis A., Ruedy R., Russell G., Cao J., & Li J. (23 May 2023) Global warming in the pipeline, IZV. ATMOS. OCEAN. PHYs. (preprint): 1–62, 39 ("With current policies, we expect
climate forcing for a few decades post-2010 to increase 0.5-0.6 W/m² 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. 25)."

12 World Meteorological Organization (2023) WMO GLOBAL ANNUAL TO DECADAL CLIMATE UPDATE, 2 (“The chance of global near-surface temperature exceeding 1.5°C above preindustrial levels for at least one year between 2023 and 2027 is more likely than not (66%). It is unlikely (32%) that the five-year mean will exceed this threshold.”). For previous years, see Madge G. (8 May 2022) Temporary breaching of 1.5°C in next five years?, UK MET OFFICE (“The chance of at least one year exceeding 1.5°C above pre-industrial levels between 2022-2026 is about as likely as not (48%). ... However, there is only a very small chance (10%) of the five-year mean exceeding this threshold.”); discussing World Meteorological Organization (2022) GLOBAL ANNUAL TO DECADAL CLIMATE UPDATE, See also Hook L. (9 May 2022) World on course to breach global 1.5C warming threshold within five years, FINANCIAL TIMES, World Meteorological Organization (2021) WMO GLOBAL ANNUAL TO DECADAL CLIMATE UPDATE, 5 (“Relative to pre-industrial conditions, the annual mean global near surface temperature is predicted to be between 0.9°C and 1.8°C higher (90% confidence interval). The chance of at least one year exceeding 1.5°C above pre-industrial levels is 44% and is increasing with time. There is a very small chance (10%) of the five-year mean exceeding this threshold. The Paris Agreement refers to a global temperature increase of 1.5°C, which is normally interpreted as the long-term warming, but temporary exceedances would be expected as global temperatures approach the threshold.”); discussed in Hodgson C. (26 May 2021) Chance of temporarily reaching 1.5C in warming is rising, WMO says, FINANCIAL TIMES; World Meteorological Organization (2020) UNITED IN SCIENCE 2020, 16 (“Figure 2 shows that in the five-year period 2020–2024, the annual mean global near surface temperature is predicted to be between 0.91 °C and 1.59 °C above pre-industrial conditions (taken as the average over the period 1850 to 1900). The chance of at least one year exceeding 1.5°C above pre-industrial levels is 24%, with a very small chance (3%) of the five-year mean exceeding this level. Confidence in forecasts of global mean temperature is high. However, the coronavirus lockdown caused changes in emissions of greenhouse gases and aerosols that were not included in the forecast models. The impact of changes in greenhouse gases is likely small based on early estimates (Le Quéré et al. 2020 and Carbonbrief.org).”); and McGuire B. (12 September 2022) Why we should forget about the 1.5C global heating target, THE GUARDIAN.

13 Hausfather Z. (28 April 2023) State of the climate: growing El Niño threatens more extreme heat in 2023, CARBONBRIEF (“Carbon Brief’s projection suggests that 2023 has the best chance of ending up as the fourth warmest year on record – and is very likely to be somewhere between the warmest year and sixth warmest year on record. We estimate that there is currently a modest chance (roughly 22%) that 2023 will end up exceeding 2016 as the warmest year on record (though if El Niño conditions continue to develop it is increasingly likely that 2024 will set a new record)...”). See also World Meteorological Organization (3 May 2023) WMO Update: Prepare for El Niño (“There is a 60% chance for a transition from ENSO-neutral to El Niño during May-July 2023, and this will increase to about 70% in June-August and 80% between July and September, according to the Update, which is based on input from WMO Global Producing Centres of Long-Range Forecasts and expert assessment. At this stage there is no indication of the strength or duration of El Niño.”).

14 Hansen J., Sato M., & Ruedy R. (12 January 2023) Global Temperature in 2022, Columbia University, 1 (“Global surface temperature in 2022 was +1.16°C (2.1°F) in the GISS (Goddard Institute for Space Studies) analysis, relative to 1880-1920, tied for 5th warmest year in the instrumental record. The current La Nina cool phase of the El Nino/La Nina cycle – which dominates year-to-year global temperature fluctuation – had maximum annual cooling effect in 2022 (Fig. 1). Nevertheless, 2022 was −0.04°C warmer than 2021, likely because of the unprecedented planetary energy imbalance (more energy coming in than going out). The already long La Nina is unlikely to continue, tropical neutral conditions are expected by Northern Hemisphere spring, with continued warming as the year progresses. Thus, 2023 should be notably warmer than 2022 and global temperature in 2024 is likely to reach +1.4-1.5°C, as our first Faustian payment of approximately +0.15°C is due.”). See also Freedman A. (19 April 2023) Rapidly developing El Niño set to boost global warming, Axios (“Hausfather echoed Adam Scaife, head of long range prediction for the U.K. Met Office. Both say the developing El Niño may cause global average surface temperatures to temporarily come very close to, or even briefly reach, the Paris Agreement’s temperature guard rail of 1.5°C (2.7°F) above pre-industrial levels.”).
arts per billion (ppb) in September 2021, the highest

National Oceanic and Atmospheric Administration Global Monitoring Laboratory, The NOAA Annual Greenhouse Gas Index (AGGI) (last visited 11 June 2023) (“For example, the atmospheric abundance of CO₂ has increased by an average of 1.88 ppm per year over the past 42 years (1979-2021). This increase in CO₂ is accelerating — while it averaged about 1.6 ppm per year in the 1980s and 1.5 ppm per year in the 1990s, the growth rate increased to 2.4 ppm per year during the last decade (2011-2021).”).

National Oceanic and Atmospheric Administration Global Monitoring Laboratory, Global carbon dioxide growth in 2018 reached 4th highest on record (last visited 11 June 2023) (“In the last two decades, the rate of increase has been roughly 100 times faster than previous natural increases, such as those that occurred at the end of the last ice age 11,000-17,000 years ago.”).

The causes of these exceptional increases are still being investigated by the global greenhouse gas science community. Analyses of measurements of the abundances of atmospheric CH₄ and its stable carbon isotope ratio δ¹³C/¹²C (reported as δ¹³C(CH₄)) (Figure 2) indicate that the increase in CH₄ since 2007 is associated with biogenic processes, but the relative contributions of anthropogenic and natural sources to this increase are unclear. While all conceivable efforts to reduce CH₄ emissions should be employed, this is not a substitute for reducing CO₂ emissions, whose impact on climate will continue for millennia.”). See also United States Department of Commerce, Global Monitoring Laboratory - Carbon Cycle Greenhouse Gases (last visited 11 June 2023); and Allen G. H. (2022) Cause of the 2020 surge in atmospheric methane clarified, Nature 612(7940): 413-414, 413 (“Its atmospheric concentration has nearly tripled since pre-industrial times, from 700 parts per billion (p.p.b.) to more than 1,900 p.p.b. today3 (see also go.nature.com/3xm1dx4). During 2007–19, the concentration rose at a rate of 7.3 ± 2.4 p.p.b. per year. Then, in 2020, the methane growth rate increased dramatically to 15.1 ± 0.4 p.p.b. per year... The concentration of atmospheric methane surged again (see go.nature.com/3xm1dx4) too 18.2 ± 0.5 p.p.b. per year in 2021 — another mysterious acceleration without a clear cause, and the fastest rate of increase ever recorded.”).

World Meteorological Organization (26 October 2022) The State of Greenhouse Gases in the Atmosphere Based on Global Observations through 2021, WMO Global Atmosphere Watch (GAW) Programme detected the largest within-year increases (15 and 18 ppb, respectively) of atmospheric methane (CH₄) since systematic measurements began in the early 1980s (Figure 1). The causes of these exceptional increases are still being investigated by the global greenhouse gas science community. Analyses of measurements of the abundances of atmospheric CH₄ and its stable carbon isotope ratio δ¹³C/¹²C (reported as δ¹³C(CH₄)) (Figure 2) indicate that the increase in CH₄ since 2007 is associated with biogenic processes, but the relative contributions of anthropogenic and natural sources to this increase are unclear. While all conceivable efforts to reduce CH₄ emissions should be employed, this is not a substitute for reducing CO₂ emissions, whose impact on climate will continue for millennia.”). See also United States Department of Commerce, Global Monitoring Laboratory - Carbon Cycle Greenhouse Gases (last visited 11 June 2023); and Allen G. H. (2022) Cause of the 2020 surge in atmospheric methane clarified, Nature 612(7940): 413-414, 413 (“Its atmospheric concentration has nearly tripled since pre-industrial times, from 700 parts per billion (p.p.b.) to more than 1,900 p.p.b. today3 (see also go.nature.com/3xm1dx4). During 2007–19, the concentration rose at a rate of 7.3 ± 2.4 p.p.b. per year. Then, in 2020, the methane growth rate increased dramatically to 15.1 ± 0.4 p.p.b. per year... The concentration of atmospheric methane surged again (see go.nature.com/3xm1dx4) too 18.2 ± 0.5 p.p.b. per year in 2021 — another mysterious acceleration without a clear cause, and the fastest rate of increase ever recorded.”).

Peng S., Lin X., Thompson R. L., Xi Y., Liu G., Hauglustaine D., Lan X., Poulet 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 CH₄ emissions–climate models. We also show that the decrease in atmospheric CH₄ sinks, which resulted from a reduction of tropospheric OH owing to less NOₓ 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 CH₄ 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): 094003, 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 NOx 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."

20 National Oceanic and Atmospheric Administration (5 April 2023) *Greenhouse gases continued to increase rapidly in 2022* (“Atmospheric methane, which is far less abundant but much more potent than CO₂ at trapping heat in the atmosphere, increased to an average of 1,911.9 parts per billion (ppb). The 2022 methane increase was 14.0 ppb, the fourth-largest annual increase recorded since NOAA’s systematic measurements began in 1983, and follows record growth in 2020 and 2021. Methane levels in the atmosphere are now more than two and a half times their pre-industrial level.”). See also National Oceanic and Atmospheric Administration Global Monitoring Laboratory (2023) *Global CH₄ Monthly Means* (last visited 11 June 2023) (Preliminary data posted on 5 April 2023 showed atmospheric CH₄ concentrations in December 2022 reached 1924.99 ppb compared with 1908.84 ppb in December 2021.).

21 National Oceanic and Atmospheric Administration (5 April 2023) *Greenhouse gases continued to increase rapidly in 2022* (“In 2022, levels of the third-most significant anthropogenic greenhouse gas, nitrous oxide, rose by 1.24 ppb to 335.7 ppb, which is tied with 2014 as the third-largest jump since 2000 and a 24% increase over its pre-industrial level of 270 ppb. The two years of highest growth occurred in 2020 and 2021. Increases in atmospheric nitrous oxide during recent decades are mainly from use of nitrogen fertilizer and manure from the expansion and intensification of agriculture.”).

22 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.”); discussed in Bekiempis V. (17 June 2021) *Earth is trapping ‘unprecedented’ amount of heat, Nasa says*, THE GUARDIAN. See also 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 EET 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.”).

23 University College London (28 September 2020) *66 Million Years of Earth’s Climate Changes Revealed in Unprecedented Detail From Ocean Sediments*, SCITECHDAILY (“Co-author Dr. Anna Joy Drury (UCL Earth Sciences), said: “We use CENOGRID to understand what Earth’s normal range of natural climate change and variability is and how quickly Earth recovered from past events. While we show that the Earth previously experienced warm climate states, these were characterized by extreme climate events and were radically different from our modern world. Since the peak warmth of the Hothouse, Earth’s climate has gradually cooled over the last 50 million years, but the present and predicted rapid anthropogenic changes reverse this trend and, if unabated, far exceed the natural variability of the last 66 million years. CENOGRID’s window into the past provides context for the ongoing anthropogenic change and how exceptional it is.””); discussing 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.
The likely range of total humaninduced climatic 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.”).
In the models, an increase in the frequency and persistence of double jet stream states over Eurasia. We find that double jet occurrences are particularly important for western European heatwaves, explaining up to 35% of temperature variability. The upward trend in the persistence of double jet events explains almost all of the accelerated heatwave trend in western Europe, and about 30% of it over the extended European region. Those findings provide evidence that in addition to thermodynamical drivers, atmospheric dynamical changes have contributed to the increased rate of European heatwaves, with implications for risk management and potential adaptation strategies.”)

29 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, 1 (“Looking into the future, in a world with 2°C of global warming (0.8°C warmer than today which at current emission levels would be reached as early as the 2040s), this event would have been another degree hotter. An event like this -- currently estimated to occur only once every 1000 years, would occur roughly every 5 to 10 years in that future world with 2°C of global warming.”).

30 Vautard R., et al. (2020) Human contribution to the record-breaking June and July 2019 heatwaves in Western Europe, ENVIRON. RES. LETT. 15(9): 094077, 1–9, 5 (“For the France average, the heatwave was an event with a return period estimated to be 134 years. As for the June case, except for HadGEM-3A, which has a hot and dry bias, the changes in intensity are systematically underestimated, as they range from 1.1 °C (CNRM-CM6.1) to 1.6 °C (EC-EARTH). By combining information from models and observations, we conclude that the probability of such an event to occur for France has increased by a factor of at least 10 (see the synthesis in figure 3). This factor is very uncertain and could be two orders of magnitude higher. The change in intensity of an equally probable heatwave is between 1.5 degrees and 3 degrees. We found similar numerical results for Lille, with however an estimate of change in intensity higher in the observations, and models predict trend estimates that are consistently lower than observation trends, a fact that needs further investigation beyond the scope of this attribution study. We conclude for these cases that such an event would have had an extremely small probability to occur (less than about once every 1000 years) without climate change in France. Climate change had therefore a major influence to explain such temperatures, making them about 100 times more likely (at least a factor of ten).”)

31 Copernicus Atmosphere Monitoring Service (4 August 2021) Copernicus: Mediterranean region evolves into wildfire hotspot, while fire intensity reaches new records in Turkey, Press Release (“With Southeast Europe currently experiencing heatwave conditions, the fire danger remains high in the area, especially across much of Turkey and around the Mediterranean. CAMS data show that the daily total Fire Radiative Power (FRP) for Turkey has reached unprecedented values in the entire dataset, which goes back to 2003.”).

32 Rousi E., Kornhuber K., Beobide-Arusuaga G., Luo F., & Coumou D. (2022) Accelerated western European heatwave trends linked to more-persistent double jets over Eurasia, NAT. COMMUN. 13(3851): 1–11, 1 (“Persistent heat extremes can have severe impacts on ecosystems and societies, including excess mortality, wildfires, and harvest failures. Here we identify Europe as a heatwave hotspot, exhibiting upward trends that are three-to-four times faster compared to the rest of the northern midlatitudes over the past 42 years. This accelerated trend is linked to atmospheric dynamical changes via an increase in the frequency and persistence of double jet stream states over Eurasia. We find that double jet occurrences are particularly important for western European heatwaves, explaining up to 35% of temperature variability. The upward trend in the persistence of double jet events explains almost all of the accelerated heatwave trend in western Europe, and about 30% of it over the extended European region. Those findings provide evidence that in addition to thermodynamical drivers, atmospheric dynamical changes have contributed to the increased rate of European heatwaves, with implications for risk management and potential adaptation strategies.”);

33 World Weather Attribution (28 July 2022) Without human-caused climate change temperatures of 40°C in the UK would have been extremely unlikely (“Combining the results based on observational and model analysis, we find that, for both event definitions, human-caused climate change made the event at least 10 times more likely. In the models,
the same event would be about 2°C less hot in a 1.2°C cooler world, which is a much smaller change in intensity than observed.”).

34 Climate Crisis Advisory Group (25 August 2022) Record-breaking heatwave will be an average summer by 2035, latest Met Office Hadley Centre data shows, Press Release (“The record-breaking heatwave experienced across Europe this summer will be considered an “average” summer by 2035, even if countries meet their current climate commitments so far agreed in negotiations under the 2015 Paris Agreement. That’s according to the latest data from the Met Office Hadley Centre, commissioned by the Climate Crisis Advisory Group (CCAG). The data (figure 1 below) looks at how rapidly temperatures are changing across Europe and tracks observed mean summer temperatures since 1850 against model predictions. It finds that, according to current predictions[1], an average summer in central Europe by 2100 will be over 4°C hotter than it was in the pre-industrial era.”); discussed in Mathers M. (25 August 2022) UK’s record-breaking heatwave will be average summer by 2035, Met Office says, INDEPENDENT.

35 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.

36 Balch J. K., Abatzoglou J. T., Joseph M. B., Koontz M. J., Mahood A. L., McGlinchy J., Cattau M. E., & Williams A. P. (2022) Warming weakens the night-time barrier to global fire, NATURE 602: 442–448, 442 (“Night-time provides a critical window for slowing or extinguishing fires owing to the lower temperature and the lower vapour pressure deficit (VPD). However, fire danger is most often assessed based on daytime conditions[1,2], capturing what promotes fire spread rather than what impedes fire. Although it is well appreciated that changing daytime weather conditions are exacerbating fire, potential changes in night-time conditions—and their associated role as fire reducers—are less understood. Here we show that night-time fire intensity has increased, which is linked to hotter and drier nights. Our findings are based on global satellite observations of daytime and night-time fire detections and corresponding hourly climate data, from which we determine landcover-specific thresholds of VPD (VPD), below which fire detections are very rare (less than 95 per cent modelled chance). Globally, daily minimum VPD increased by 25 per cent from 1979 to 2020. Across burnable lands, the annual number of flammable night-time hours—when VPD exceeds VPD—increased by 110 hours, allowing five additional nights when flammability never ceases. Across nearly one-fifth of burnable lands, flammable nights increased by at least one week across this period. Globally, night fires have become 7.2 per cent more intense from 2003 to 2020, measured via a satellite record. These results reinforce the lack of night-time relief that wildfire suppression teams have experienced in recent years. We expect that continued night-time warming owing to anthropogenic climate change will promote more intense, longer-lasting and larger fires.”); discussed in Dickie G. (19 July 2022) Steamy nights in European heatwave worsen health and fire risks – experts, REUTERS.
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.

38 Pinto I., et al. (2022) Climate change exacerbated rainfall causing devastating flooding in Eastern South Africa, WORLD WEATHER ATtribution: 1–21, 2 (“40,000 people were impacted by the rainfall and subsequent floods- 435 deaths were reported from the affected areas, 55 injured and 54 people missing (Government of South Africa, 2022a). At least 13,500 houses were damaged or destroyed - among these, over 4,000 homes in informal settlements in eThekwini Metropolitan Municipality were destroyed, leaving 6278 people homeless and 7245 people in shelters (ibid.). 630 schools were affected in the KZN province in the impacted areas, and 124 schools damaged, thus impacting around 270,000 students (Government of South Africa, 2022b). Critical infrastructure such as bridges and roads were also severely damaged, including two major highways (IFRC, 2022), and the mobile phone infrastructure of KwaZulu-Natal saw 400 towers impacted due to power outages and flooded fibre conduit (Tech Central, 2022). In addition, large parts of Durban were left without electricity and water for days due to damage to water treatment and power plant stations (IFRC, 2022). The overall property damage is estimated around 17 billion rand/US$1.57 billion (IOL, 2022a).”;

39 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.

40 Fischer E. M., Sippel S., & Knutti R. (2021) Increasing probability of record-shattering climate extremes, NAT. CLIM. CHANGE 11: 689–685, 689 (“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. In 2051–2080, such events are estimated to occur about every 6–37 years somewhere in the northern midlatitudes.”).

41 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.”).

42 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).”).

43 Hansen J. E., Sato M., Simons L., Nazarenko L. S., Sangha I., von Schuckmann K., Loeb N. G., Osman M. B., Jin Q., Kharecha P., Tselioudis G., Jeong E., Lacis A., Ruedy R., Russell G., Cao J., & Li J. (23 May 2023) Global warming in the pipeline, IZV. ATMOS. OCEAN. PHYS. (preprint): 1–62, 13 (“If ECS is 4°C (1°C per W/m²), more warming is in the pipeline than widely assumed. GHG forcing today already exceeds 4 W/m². Aerosols reduce the net forcing to about 3 W/m², based on IPCC estimates (Section 5), but warming still in the pipeline for 3 W/m² forcing is 1.8°C, exceeding warming realized to date (1.2°C). Slow feedbacks increase the equilibrium response even further (Section 6). Large warmings can be avoided via a reasoned policy response, but definition of effective policies will be aided by an understanding of climate response times.”); 1 (“Equilibrium global warming including slow feedbacks for today’s human-made greenhouse gas (GHG) climate forcing (4.1 W/m²) is 10°C, reduced to 8°C by today’s aerosols. 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. Under the current geopolitical approach to GHG emissions, global warming will likely pierce the 1.5°C ceiling in the 2020s and 2°C before 2050. Impacts on people and nature will accelerate as global warming pumps up hydrologic extremes.”); 41 (“One merit of consistent analysis for the full Cenozoic era is revelation that the human-made climate forcing exceeds the forcing at transition from a largely ice-free planet to glaciated Antarctica, even with inclusion of a large, negative, aerosol climate forcing. Equilibrium global warming for today’s GHG level is 10°C for our central estimate ECS = 1.2°C ± 0.2°C per W/m², including the amplifications from disappearing ice sheets and non-CO₂ GHGs (Sec. 4.4). Aerosols reduce equilibrium warming to about 8°C. Equilibrium sea level change is + 60 m (about 200 feet).”).

44 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).”).
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 Khourdjai E., 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.”). 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.), 822 (“Additional methane and BC mitigation would contribute to offsetting the additional warming associated with SO2 reductions that would accompany decarbonization (high confidence.”); Ramanathan V. & Feng Y. (2008) *On avoiding dangerous anthropogenic interference with decarbonization: Formidable challenges ahead*, PROC. NAT’L ACAD. SCI. 105(38): 14245–14250, 14248 (“Switching from coal to “cleaner” natural gas will reduce CO2 emission and thus would be effective in 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 CO2 emissions, as for the CO2-measures scenario, does little to mitigate warming until after the next 20-30 years (Box 6.2). In fact, sulphur dioxide (SO2) is coemitted with CO2 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 CO2-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 CO2 emissions in the past. The CO2-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 CH4 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 CO2 measures, so that the emissions reductions of the short-lived pollutants are almost identical regardless of whether the CO2 measures are implemented or not, as shown in Chapter 5. The near-term measures and the CO2 measures also impact climate change over different timescales owing to the different lifetimes of these substances. In essence, the near-term CH4 and BC measures are effectively uncoupled from CO2 measures examined here.”); and Wanser K., Wong A., Karspeck A., & Esquerra N. (2023) *NEAR-TERM CLIMATE RISK AND INTERVENTION: A ROADMAP FOR RESEARCH, U.S. RESEARCH INVESTMENT, AND INTERNATIONAL SCIENTIFIC COOPERATION*, SilverLining, 12 (“Particles (i.e., aerosols) in the atmosphere generally increase the total amount of sunlight reflected to space by scattering incoming sunlight. Anthropogenic activities produce both GHGs and other particulate matter; while GHGs warm climate, aerosols have a cooling effect both by directly scattering sunlight (i.e., the aerosol direct effect) and indirectly as the aerosols interact with clouds, increasing their brightness and/or their duration (i.e., the cloud–aerosol effect) … The potential global cooling effect of all anthropogenic aerosols is estimated at 0.5–1.1°C (see Figure 6). Thus, these effects are potentially very large while also serving as a large source of uncertainty, making reducing these uncertainties among the highest priorities for climate research, particularly in the context of assessing near-term climate risk. Particles from emissions produced by human activities are also associated with significant adverse health and environmental effects. Actions are ongoing around the world to substantially reduce them, including recent regulation to substantially reduce sulfate emissions from ships. As the world reduces these particulate emissions, the loss of this cooling “shield” could lead to rapid substantial warming.”).

International Energy Agency (2023) *CREDIBLE PATHWAYS TO 1.5 °C - FOUR PILLARS FOR ACTION IN THE 2020s*, 1–15, 3 (“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 CO₂ emissions reductions from the land-use sector. Tackling non-CO₂ emissions is vital to limiting peak warming. Assuming strong action on CO₂, meeting or exceeding commitments like the Kigali Amendment on HFCs and the Global Methane Pledge, and acting on non-CO₂ 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 CO₂ by 2030 need to be implemented, against the roughly 0.3 Gt CO₂ 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.”; 11 (“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 CO₂ 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 CO₂ emissions across the supply chain to the fullest extent practicable.”).

47 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 CO₂ 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-CO₂ 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 CO₂ 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-ten years, and produce a climate response within the next decade or two.”).

48 Armstrong McKay D. I., Staal A., Abrams J. F., Winkelmann R., Sakshewski 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 regional after 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. 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. We argue that cascading effects might be common. Research last year 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. 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., & Yassa 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.”).  

49 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
livelhood 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 CO₂) 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.”. 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, 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)”); 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.”); 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).”); and Berwyn B. (14 February 2023) Sea Level Rise Could Drive 1 in 10 People from Their Homes, with Dangerous Implications for International Peace, UN Secretary General Warns, Inside Climate News.

50 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

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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*).”). See also Fischer E. M., Sippel S., & Knutti R. (2021) *Increasing probability of record-shattering climate extremes*, Nat. Clim. Change 11: 689–695, 689 (“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.”).  

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 CO2 equivalent (PgCO2e) 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 PgCO2e y⁻¹) represents cost-effective climate mitigation, assuming the social cost of CO2 pollution is ≥100 USD MgCO2e⁻¹ by 2030. Natural climate solutions can provide 37% of cost-effective CO2 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 MgCO2⁻¹. 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.

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.”).

based on Supplementary Data 1 ("Country-level results for population, land area and land fraction exposed to MAT > 29°C"). By the 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."

5-6 ("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., Lenten 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.").

54 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 CO2 emissions are reduced compared to modelled 2019 emissions by 27% [11–46%] in 2030 and by 52% [36-70%] in 2040; and global CH4 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 CO2 emissions are reduced compared to modelled 2019 emissions by 48% [36–69%] in 2030 and by 80% [61–109%] in 2040; and global CH4 emissions are reduced by 34% [21–57%] in 2030 and 44% [31-63%] in 2040. There are similar reductions of non-CO2 emissions by 2050 in both types of pathways: CH4 is reduced by 45% [25–70%]; N2O 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 CH4 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 CH4 could further reduce peak warming. (high confidence) (Figure SPM.5)").

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-CO₂ GHG emissions at the time of net zero CO₂ are projected to be of similar magnitude in modelled pathways that limit warming to 2°C (>67%) or lower. These non-CO₂ GHG emissions are about 8 [5–11] GtCO₂-eq per year, with the largest fraction from CH₄ (60% [55–80%]), followed by N₂O (30% [20–35%]) and F-gases (3% [2–20%]). [FOOTNOTE 52] Due to the short lifetime of CH₄ in the atmosphere, projected deep reduction of CH₄ emissions up until the time of net zero CO₂ in modelled mitigation pathways effectively reduces peak global warming. (high confidence)

56 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 CO₂ 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 GtCO₂ over the 21st century.”).

57 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. 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. We argue that cascading effects might be common. Research last year 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. 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).”).

58 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 (“Abrupt change is defined as a change in the system that is substantially faster than the typical rate of the changes in its history (Chapter 1, Section 1.4.5). A related matter is a tipping point: a critical threshold beyond which a system reorganizes, often abruptly and/or irreversibly.”).

59 Drijfhout S., Bathany 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. ACADEM. SCI. 112(43): E5777–E5786, E5777 (“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°C, 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-Delmonte 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., Fyle 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-Delmonte V., et al. (eds.), 4-96 (Table 4.10 lists 15 components of the Earth system susceptible to tipping points).
Impacts of 1.5°C of Global Warming on Natural and Human Systems, Arias P., Grime J., & Yassaa N. (eds.), 42 (“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 CYROSHERE 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°C 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 2°C (IPCC, 2018).”)

60 See Hoegh-Gulberg 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 CYROSHERE 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°C 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 2°C (IPCC, 2018).”)

61 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) 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.” 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.”); 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., Eligozouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Úrge-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 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 Some of its mechanisms resemble those of the Dansgaard–Oschger 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.”); *and* Spratt D. & Dunlop I. (2017) *What lies beneath? The scientific understatement of climate risks*, 21 (“As discussed above, climate models are not yet good at dealing with tipping points. This is partly due to the nature of tipping points, where a particular and complex confluence of factors abruptly change a climate system characteristic and drive it to a different state. To model this, all the contributing factors and their forces have to be well identified, as well as their particular interactions, plus the interactions between tipping points. Researchers say that “complex, nonlinear systems typically shift between alternative states in an abrupt, rather than a smooth manner, which is a challenge that climate models have not yet been able to adequately meet.”).

63 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 state11. Interactions could happen through ocean and atmospheric circulation or through feedbacks that increase greenhouse-gas levels and global temperature.”). *See also* 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.”); *Klose A. K., Wunderling N., Winkelmann R., & Donges J. F. (2021) What do we mean.*
Abrupt and Extreme Climate Events

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; McNeill 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-CO2 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 CO2) 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% of IPCC models do not include carbon emissions from permafrost thaw.

65 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.”).

66 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 ± 0.35 W·m⁻²·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.”).

67 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 CO₂ levels rise above 1,200 ppm. In addition to the warming from rising CO₂ 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. If we assume a climate sensitivity parameter of 1.2 K (W m⁻²)⁻¹ (as for the more sensitive among current GCMs), this implies (110 – 10) W m⁻² × 6.5% × 1.2 K (W m⁻²)⁻¹ ≈ 8 K global-mean surface warming when subtropical marine stratocumulus break up.”).

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’s land 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.”).

69 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 (“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.).”); 4 (“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.”); 4-5 (“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 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.”).
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 into the atmosphere, contributing to further warming. Changes in the Arctic also affect the brightness of the surface, which influences warming. As the Arctic atmosphere warms, it can hold more water vapor, which is an important greenhouse gas.

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.

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). 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).

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.").

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). … Using a criterion based on the speed of near-surface air temperature warming over the past four decades, we find that the current Arctic is experiencing rates of warming comparable to abrupt changes, or D–O events, recorded in Greenland ice cores during the last glacial period. [During the last glacial period (120,000–11,000 years ago), more than 20 abrupt periods of warming, known as Dansgaard–Oeschger (D–O) events, took place.] Both past changes in the Greenland ice cores and the ongoing trends in the Arctic are directly linked to sea-ice retreat—in the Nordic Seas during glacial times and in the Eurasian Arctic at present. Abrupt changes have already been experienced and could, according to state-of-the-art climate models, occur in the Arctic during the twenty-first century, but climate models underestimate current rates of change in this region.").

Observational determination of albedo decrease caused by vanishing Arctic sea ice. PROQ. 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 CO₂ 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 CO₂, 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.”).

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. 4e). In addition, continuing weakening of the cold halocline in the Siberian sector also influenced the upper ocean heat content 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 (“The study’s authors said that would take a long time even under the most optimistic global warming and emissions reduction scenarios. Even if carbon dioxide emissions fell to zero sometime in the next 50 years, it would take decades more for the ocean to lose all the heat it has accumulated since humans began burning fossil fuels and emitting greenhouse gases.”).

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 values occur in the sea areas near Novaya Zemlya, which were locally warming up to seven times as fast as the global average. These high warming rates are consistent with recent research, and evidently, the primary reason for such a high amplification ratio is the reduction of cold-season ice cover, which has been most pronounced in the Barents Sea. Furthermore, it has been found that changes in atmospheric circulation have amplified the warming in this area. In general, there are no regions within the Arctic Circle where AA 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; and Fountain H. (11 August 2022) Arctic Warming Is Happening Faster Than Described, Analysis Shows, THE NEW YORK TIMES. See also Jacobs P., Lenssen N. J. L., Schmidt G. A., & Rohde R. A. (2021) The Arctic Is Now Warming Four Times As Fast As The Rest of the Globe, Presentation at the American Geophysical Union Fall Meeting, A13E-02 (“We demonstrate the Arctic is likely warming over 4 times faster than the rest of the world, some 3-4 times the global average, with higher rates found both for more recent intervals as well as more accurate latitudinal boundaries. These results stand in contrast to the widely-held conventional wisdom — prevalent across scientific and lay publications alike — that the Arctic is "only" warming around twice as fast as the global mean.”); discussed in Voosen P. (14 December 2021) The Arctic is warming four times faster than the rest of the world, SCIENCE.

Human-caused climate change fuels warmer, wetter, stormier Arctic (“Arctic annual air temperatures from October 2021 to September 2022 were the sixth warmest dating back to 1900, continuing a decades-long trend in which Arctic air temperatures have warmed faster than the global average. The Arctic's seven warmest years since 1900 have been the last seven years.”).
September monthly extent has been decreasing at an average rate of −82,700 km² per year since 1979 (−13.1% per decade relative to the 1981–2010 average; Fig. 5.8c).

78 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, 4, 6 (“In the high-emission scenario, five out of six selection criteria that include ocean heat transport provide a first ice-free Arctic in September before 2040 (range of multi-model means: 2032–2039), more than 20 years before the date of ice-free Arctic for the multi-model mean without model selection (i.e. 2061)”; “This model selection reveals that sea-ice area and volume reach lower values at the end of this century compared to the multi-model mean without selection. This arises both from a more rapid reduction in these quantities through this century and from a lower present-day sea-ice area. Using such a model selection, the timing of an almost ice-free Arctic in summer is advanced by up to 29 years in the high-emission scenario, i.e. it could occur as early as around 2035.”). *See also* 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, 17 (“Excluding the values later than 2100, the averaged projected [first ice-free Arctic summer year (FIASY)] value for RCP4.5 was 2054 with a spread of 74 years; for RCP8.5, the averaged FIASY was 2042 with a spread of 42 years. ...which put the mean FIASY at 2037. The RCP8.5 projections tended to push FIASY earlier, except for those of the MICRO-ESM and MICRO-ESM-CHEM models. Those two models also tended to project earlier Arctic ice-free dates and longer durations.”); and Overland J. E. & Wang M. (2013) *When will the summer Arctic be nearly sea ice free?*, GEOPHYS. RES. LETT. 40(10): 2097–2101, 2097 (“Three recent approaches to predictions in the scientific literature are as follows: (1) extrapolation of sea ice volume data, (2) assuming several more rapid loss events such as 2007 and 2012, and (3) climate model projections. Time horizons for a nearly ice-free summer for these three approaches are roughly 2020 or earlier, 2030 ± 10 years, and 2040 or later. Loss estimates from models are based on a subset of the most rapid ensemble members. … Observations and citations support the conclusion that most global climate model results in the CMIP5 archive are too conservative in their sea ice projections. Recent data and expert opinion should be considered in addition to model results to advance the very likely timing for future sea ice loss to the first half of the 21st century, with a possibility of major loss within a decade or two.”).

79 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/m² is approximately equivalent to the direct radiative effect of emitting one trillion tons of CO₂ into the atmosphere (see calculation in Appendix A). As of 2016, an estimated 2.4 trillion tons of CO₂ 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 CO₂ 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 CO₂ emissions at the current rate.”). *See also* Institute for Governance & Sustainable Development (2019) *Plain Language Summary of Pistone K., et al.*

80 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.”).

81 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 transport volume 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).

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.”).

Zhang J., Lindsay R., Schweiger A., & Steele M. (2013) *The impact of an intense summer cyclone on 2012 Arctic sea ice retreat*, GEOFYPH. 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 1j). 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. GEOFYPH. RES. ATOMOS. 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.

Rantanen M., Karpechko A. Y., Lipponen A., Nordin K., Hyvärinen O., Ruosteenkoja 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 values occur in the sea areas near Novaya Zemlya, which were locally warming up to seven times as fast as the global average. These high warming rates are consistent with recent research44, and evidently, the primary reason for such a high amplification ratio is the reduction of cold-season ice cover, which has been most pronounced in the Barents Sea44,45. Furthermore, it has been found that changes in atmospheric circulation have amplified the warming in this area46,47. In general, there are no regions within the Arctic
Circle where AA 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; and Fountain H. (11 August 2022) Arctic Warming Is Happening Faster Than Described, Analysis Shows, The New York Times. See also Jacobs P., Lenssen N. J. L., Schmidt G. A., & Rohde R. A. (2021) The Arctic Is Now Warming Four Times As Fast As the Rest of the Globe. Presentation at the American Geophysical Union Fall Meeting, A13E-02 (“We demonstrate the Arctic is likely warming over 4 times faster than the rest of the world, some 3–4 times the global average, with higher rates found both for more recent intervals as well as more accurate latitudinal boundaries. These results stand in contrast to the widely-held conventional wisdom — prevalent across scientific and lay publications alike — that the Arctic is "only" warming around twice as fast as the global mean.”); discussed in Voosen P. (14 December 2021) The Arctic Is warming four times faster than the rest of the world, Science; and Chylek P., Folland C., Klett J. D., Wang M., Hengartner N., Lesins G., & Dubey M. K. (2022) Annual Mean Arctic Amplification 1970–2020: Observed and Simulated by CMIP6 Climate Models, Geophys. Res. Lett. 49(13): 1–8, 1 (“While the annual mean Arctic Amplification (AA) index varied between two and three during the 1970–2000 period, it reached values exceeding four during the first two decades of the 21st century. The AA did not change in a continuous fashion but rather in two sharp increases around 1986 and 1999. During those steps the mean global surface air temperature trend remained almost constant, while the Arctic trend increased. Although the “best” CMIP6 models reproduce the increasing trend of the AA in 1980s they do not capture the sharply increasing trend of the AA after 1999 including its rapid step-like increase. We propose that the first sharp AA increase around 1986 is due to external forcing, while the second step close to 1999 is due to internal climate variability, which models cannot reproduce in the observed time…. Annual mean Arctic Amplification (AA) within the period 1970–2020 changed in steep steps around 1986 and 1999. It reached values over 4.0…”); discussed in Los Alamos National Laboratory (5 July 2022) Arctic temperatures are increasing four times faster than global warming, Phys.Org.

85 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 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° 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.”).

86 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. (2022) 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).”).

87 Ciavarella A., et al. (2021) Prolonged Siberian heat of 2020 almost impossible without human influence, Clim. Change 166(9): 1–18, 1 (“Over the first half of 2020, Siberia experienced the warmest period from January to June since records began and on the 20th of June the weather station at Verkhoyansk reported 38 °C, the highest daily maximum temperature recorded north of the Arctic Circle… We show that human-induced climate change has dramatically increased the probability of occurrence and magnitude of extremes in both of these (with lower confidence for the probability for Verkhoyansk) and that without human influence the temperatures widely experienced in Siberia in the first half of 2020 would have been practically impossible.”). See also DeGeorge K. (24 June 2021) Siberia is seeing record heat — again, Arctic Today (“On Monday, satellites with the European Union’s Copernicus Earth observation program detected exceptionally high ground temperatures across much of the region, with a high reaching an astounding 48 degrees Celsius (118 degrees Fahrenheit) near Verkhoyansk, in the Sakha Republic, while other sites recorded highs of 43 degrees C (109.4 degrees F) and 37 degrees C (98.6 degrees F). It’s important to note that those are ground temperatures, not air temperatures. For example, that latter figure was recorded in Saskylakh, also in the Sakha Republic, where air temperatures taken at the same time were a slightly cooler 31.9 degrees C (89.4 degrees F). That still set a record for Saskylakh, though, as the hottest pre-solstice temperature...
The news comes a month after the Arctic Council’s Arctic Monitoring and Assessment working group issued a report confirming that the region is now warming three times faster than the global average, rather than twice as fast. And it comes almost exactly a year after the first 100-degree (Fahrenheit) temperature was recorded north of the Arctic Circle — also in Verkhoyansk.

Schweiger A. J., Steele M., Zhang J., Moore G. W. K., & Laird 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 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.”).

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 in all regions eventually falls below 0.5 m during the 21st century.”).

Schweiger A. J., Steele M., Zhang J., Moore G. W. K., & Laird 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 (Odobenus rosmarus) throughout the 21st century.”).

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\(^2\). Przybylak and Wyszyński\(^2\) 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 observations from northern and eastern Svalbard and from FJL, we were able to additionally study the regional SAT developments in the NBS. 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.

92 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.

93 Arctic Monitoring and Assessment Programme (2021) ARCTIC CLIMATE CHANGE UPDATE 2021: KEY TRENDS AND IMPACTS, SUMMARY FOR POLICY-MAKERS, 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.”). See also Druckenmiller M. L., et al. (2021) The Arctic, BULL. AM. MET. SOC. 102(8): S263–S316, S280 (“September is the month when the minimum annual sea ice extent occurs. In 2020, this average monthly ice extent was 3.92 million km² (Fig. 5.8b), the second lowest monthly extent in the 42-year satellite record. On 15 September, the annual minimum Arctic sea ice extent of 3.74 million km² was reached; this was also the second lowest on record. The September monthly extent has been decreasing at an average rate of ~82,700 km² per year since 1979 (~13.1% per decade relative to the 1981–2010 average; Fig. 5.8c.”).

94 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, 4, 6 (“In the high-emission scenario, five out of six selection criteria that include ocean heat transport provide a first ice-free Arctic in September before 2040 (range of multi-model means: 2032–2039), more than 20 years before the date of ice-free Arctic for the multi-model mean without model selection (i.e. 2061)”; “This model selection reveals that sea-ice area and volume reach lower values at the end of this century compared to the multi-model mean without selection. This arises both from a more rapid reduction in these quantities through this century and from a lower present-day sea-ice area. Using such a model selection, the timing of an almost ice-free Arctic in summer is advanced by up to 29 years in the high-emission scenario, i.e. it could occur as early as around 2035.”). See also 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, 17 (“Excluding the values later than 2100, the averaged projected [first ice-free Arctic summer year (FIASY)] value for RCP4.5 was 2054 with a spread of 74 years; for RCP8.5, the averaged FIASY was 2042 with a spread of 42 years. ...which put the mean FIASY at 2037. The RCP8.5 projections tended to push FIASY earlier, except for those of the MICRO-ESM and MICRO-ESM-CHEM models. Those two models also tended to project earlier Arctic ice-free dates and longer durations.”); and Overland J. E. & Wang M. (2013) When will the summer Arctic be nearly sea ice free?, GEOPHYS. RES. LETT. 40(10): 2097–2101, 2097 (“Three recent approaches to predictions in the scientific literature are as follows: (1) extrapolation of sea ice volume data, (2) assuming several more rapid loss events such as 2007 and 2012, and (3) climate model projections. Time horizons for a nearly sea-free summer for these three approaches are roughly 2020 or earlier, 2030 ± 10 years, and 2040 or later. Loss estimates from models are based on a subset of the most rapid ensemble members. … Observations and citations support the conclusion that most global climate model results in the CMIP5 archive are too conservative in their sea ice projections. Recent data and expert opinion should be considered in addition to model results to advance the very likely timing for future sea ice loss to the first half of the 21st century, with a possibility of major loss within a decade or two.”).

95 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/m² relative to the 1979 baseline state. This is equivalent to the effect of one trillion tons of CO₂ emissions. These results suggest that the additional heating due to complete Arctic sea ice loss would hasten global warming by an estimated 25 years.”).
The minimum ice extent is the second lowest in the 42-year-old satellite record, reinforcing the 14 lowest extents in the satellite record melt season, and discuss the Antarctic winter sea ice growth, in early October. …The 14 lowest extents in the satellite era have all occurred in the last 14 years."). See also Richter-Menge J., Druckenmiller M. L. & Thoman R. L. (2020) 15 Years of Arctic Observation: A Retrospective, in ARCTIC REPORT CARD 2020, Thomas R. L., Richter-Menge J., & Druckenmiller M. L. (eds.), National Oceanic and Atmospheric Administration, 8 (“As it turns out, the first publication in 2006 coincided with a cusp of transformation in the sea ice cover, which is literally and figuratively central to the Arctic system. The 2007 September minimum sea ice extent stunned scientists and grabbed world-wide media attention with a new record minimum that was 23% below the previous record low set in 2005. Just five years later, in 2012, the 2007 record was overtaken by a September minimum sea ice extent that was 18% below 2007. The 2012 record low still stands as of 2020. However, in the 14 years since ARC2006 the late summer sea ice minimum extent has never returned to pre-2007 values.

99 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, 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. 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.

98 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, 18 (“Over 1982–2020, AICA SIV decreased to 20,679.0 km3 in 2020 from 51,216.6 km3 in 1982, resulting in a 60% decrease at a rate of −859.2 km3 per year in March. In September, AICA SIV declined to 2462.0 km3 in 2020 from 8931.2 km3 in 1982, resulting in a 72% decrease at a rate of −170.2 km3 per year. Based on an annual average, AICA SIV decreased by 17,284.8 km3, which is 63% of the 27,590.4 km3 in 1982, resulting in 10,305.5 km3 SIV in 2020. PICA SIV and SICA SIV declined to 5766.0 km3 and 4522.8 km3 in 2020 from 20,313.0 km3 and 7271.0 km3 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.

97 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, 12 (“As it turns out, the first publication in 2006 coincided with a cusp of transformation in the sea ice cover, which is literally and figuratively central to the Arctic system. The 2007 September minimum sea ice extent stunned scientists an

96 National Aeronautics and Space Administration, Arctic Sea Ice Minimum Extent (last visited 14 February 2023) (“Arctic sea ice reaches its minimum extent (the area in which satellite sensors show individual pixels to be at least 15% covered in ice) each September. September Arctic sea ice is now shrinking at a rate of 12.6% per decade, compared to its average extent during the period from 1981 to 2010.

95 National Snow and Ice Data Center (21 September 2020) Arctic sea ice decline stalls out at second lowest minimum (“On September 15, Arctic sea ice likely reached its annual minimum extent of 3.74 million square kilometers (1.44 million square miles). The minimum ice extent is the second lowest in the 42-year-old satellite record, reinforcing the long-term downward trend in Arctic ice extent. Sea ice extent will now begin its seasonal increase through autumn and winter. …Please note that this is a preliminary announcement. Changing winds or late-season melt could still reduce the Arctic ice extent, as happened in 2005 and 2010. NSIDC scientists will release a full analysis of the Arctic melt season, and discuss the Antarctic winter sea ice growth, in early October. …The 14 lowest extents in the satellite era have all occurred in the last 14 years.

63
Along with the significant decrease in the MY ice area, there has been a decline from about two million square kilometers (780,000 square miles) in 1980 to 0.09 million km² in March 2020. The 2021 minimum was the twelfth lowest in the nearly 43-year satellite record. The last 15 years are the lowest 15 sea ice extents in the satellite record. The amount of multi-year ice (ice that has survived at least one summer melt season), is one of the lowest levels in the ice age record, which began in 1984.”.

See also Druckenmiller M. L., et al. (2021) Sea Ice, in ARCTIC REPORT CARD 2020, Thomas R. L., Richter-Menge J., & Druckenmiller M. L. (eds.), National Oceanic and Atmospheric Administration, 29–30, 48 (“The oldest ice (>4 years old), which once dominated within the Arctic Ocean, now makes up just a small fraction of the Arctic Ocean ice pack in March, when the sea ice cover is at its maximum extent (Fig. 3). In 1985, 33% of the ice pack was very old ice (>4 years), but by March 2019 old ice only constituted 1.2% of the ice pack within the Arctic Ocean. The total extent of the oldest ice declined from 2.52 million km² in March 1985 to 0.09 million km² in March 2019. … First-year ice now dominates the sea ice cover, comprising ~70% of the March 2019 ice pack, compared to approximately 35–50% in the 1980s. Given that older ice tends to be thicker, the sea ice cover has transformed from a strong, thick ice mass in the 1980s to a younger, more fragile, and thinner ice mass in recent years. First-year ice is therefore more vulnerable to melting out in summer, thereby increasing the likelihood of lower minimum ice extents.”); “The oldest ice (>4 years old) was once a major component of the Arctic sea ice cover, but now makes up just a small fraction of the March Arctic Ocean ice pack (Fig. 3). In 1985, 33% of the ice pack was very old ice (>4 years), but by March 2020 old ice only constituted 4.4% of the ice pack within the Arctic Ocean. The total extent of the oldest ice declined from 2.70 million km² in March 1985 to 0.34 million km² in March 2020. The March 2020 extent of >4 year old ice increased from the record-low year in 2019 when it was only 1.2% (0.09 million km²) of the ice cover. This increase was due to 3–4 year old ice surviving a year and aging into >4 year old ice. The 3–4 year old cover dropped from 6.4% in 2019 to 3.7% in 2020. Overall the percentage of ice 3 years and older was effectively unchanged. Note that these percentages are relative to ice in the Arctic Ocean region (Fig. 3, bottom inset); areas in the peripheral seas outside of this region have little or no older ice and thus do not show any change over time.”).

See also Perovich D., et al. (2020) Sea Ice, in ARCTIC REPORT CARD 2020, Thomas R. L., Richter-Menge J., & Druckenmiller M. L. (eds.), National Oceanic and Atmospheric Administration, 29–30, 48 (“The oldest ice (>4 years old), which once dominated within the Arctic Ocean, now makes up just a small fraction of the Arctic Ocean ice pack in March, when the sea ice cover is at its maximum extent (Fig. 3). In 1985, 33% of the ice pack was very old ice (>4 years), but by March 2019 old ice only constituted 1.2% of the ice pack within the Arctic Ocean. The total extent of the oldest ice declined from 2.52 million km² in March 1985 to 0.09 million km² in March 2019. … First-year ice now dominates the sea ice cover, comprising ~70% of the March 2019 ice pack, compared to approximately 35–50% in the 1980s. Given that older ice tends to be thicker, the sea ice cover has transformed from a strong, thick ice mass in the 1980s to a younger, more fragile, and thinner ice mass in recent years. First-year ice is therefore more vulnerable to melting out in summer, thereby increasing the likelihood of lower minimum ice extents.”). See also Druckenmiller M. L., et al. (2021) The Arctic, BULL. AM. MET. SOC, 102(8): S263–S316, S282 (“The dominant ice type is now first-year ice (0–1 years old), which comprised about 70% of the March 2020 Arctic Ocean ice cover. The median ice age dropped from 2–3 years old in the mid-1980s to less than 1 year old by 2020. The total extent of the oldest ice (>4 years old) declined from 2.50 million km² in March 1985 to 0.34 million km² in March 2020.”); World Meteorological Organization (2020) UNITED IN SCIENCE 2020, 9 (“Arctic (as well as sub-Arctic) sea ice has seen a long-term decline in all months during the satellite era (1979–present), with the largest relative losses in late summer, around the time of the annual minimum in September, with regional variations. The long-term trend over the 1979–2019 period indicates that Arctic summer sea-ice extent has declined at a rate of approximately 13% per decade (Figure 4). In every year from 2016 to 2020, the Arctic average summer minimum and average winter maximum sea-ice extent were below the 1981–2010 long term average. In July 2020, the Arctic sea-ice extent was the lowest on record for July. There is very high confidence that Arctic sea-ice extent continues to decline in all months of the year and that since 1979, the areal proportion of thick ice, at least 5 years old, has declined by approximately 90%).”; National Snow & Ice Data Center (2 September 2020) Tapping the brakes, Arctic Sea Ice News & Analysis (“As of September 1, Arctic sea ice extent stood at 4.26 million square kilometers (1.64 million square miles), the second lowest extent for that date in the satellite passive microwave record that started in 1979.”); and Bi H., Liang Y., Wang Y., Liang X., Zhang Z., Du T., Yu Q., Huang J., Kong M., & Huang H. (2020) Arctic multiyear sea ice variability observed from satellites: a review, J. OCEAN. LIMNOL. 38(4): 962–984, 963 (“As the MY [multiyear] ice in the Arctic Ocean is declining at a significant rate, approximately -9%–15%/decade in the past three decades (Comiso, 2012; Polyakov et al., 2012; Kwok, 2018), the MY ice area has declined from about two-thirds of the Arctic basin area to less than one third (Galley et al., 2016). Along with the significant decrease in the MY coverage and extent, there is also a clear transitioning trend in MY composition toward the thinner and younger components (Rigor and Wallace, 2004; Maslanik et al., 2007, 2011; Tschudi et al., 2016).”). Analysis by Zack Labe showed that sea ice for the high Arctic (above 80 °N) was the lowest
extents on record: see Zack Labe (@ZLabe), Twitter, 11 September 2020, 6:19pm (“Sea ice extent in the middle of the #Arctic Ocean is currently the lowest on record (e.g., high Arctic ~80°N+ latitude). This is a pretty impressive statistic.”).

103 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.”).

104 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 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 values calculated from benthic d18O) (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… 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.”).


106 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.”).

107 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.”).

108 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.”).
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 constraint on the sea ice edge. 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)."

"Most of the CMIP6 models consistently show a poleward enhanced Arctic Ocean cooling machine in a warming climate". (Shu Q., Wang Q., Song Z., & Qiao F. 2021)
The underestimated trends in sea ice—through the well-documented increase in both temperature and salinity in the entire water column. Thus, both sea and swell evolve into swells. The swells remain tied to the available fetch, however, because fetch is a proxy for the basin size. Furthermore, we show that the wave energy scales with fetch throughout the seasonal ice cycle.

Exceptional warming over the Barents sea. SCI. REP. 12(9371): 1–18, 1 (“Both the SAT analysis from instrumental records and widely used reanalyses products, including ERA5, point to a maximum warming area in the Barents region (Fig. 1). This Arctic warming hotspot is not constrained to the warming atmosphere; the Northern Barents Sea (NBS) region also hosts the most pronounced loss of Arctic winter sea ice 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. In addition, the increase in salinity is larger towards the upper layers, leading to a weakened stratification and thereby an increased upward heat flux. 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.”).

Isaksen K., et al. (2022) Exceptional warming over the Barents sea. SCI. REP. 12(9371): 1–18, 1 (“Both the SAT analysis from instrumental records and widely used reanalyses products, including ERA5, point to a maximum warming area in the Barents region (Fig. 1). This Arctic warming hotspot is not constrained to the warming atmosphere; the Northern Barents Sea (NBS) region also hosts the most pronounced loss of Arctic winter sea ice 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. In addition, the increase in salinity is larger towards the upper layers, leading to a weakened stratification and thereby an increased upward heat flux. 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.”).

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. 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. 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. Recent underwater observations made in 2003–2008 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.”).

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.”).

117 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). “). 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.

118 Mallett R. D. C., Stroeve J. C., Cornish S. B., Crawford A. D., Lukovich J. V., Serreze M. C., Barrett A. P., Meier W. N., Heorton H. D. B. S., & Tsamados M. (2021) Record winter winds in 2020/21 drove exceptional Arctic sea ice transport, COMMUN. EARTH ENVIRON. 2(149): 1–6, 2 (“The response of the sea ice to the wind forcing was such that four times as much MYI area was transported into the Beaufort Sea as was transported out, but the total ice area transported out was double that transported in (Fig. 2a, b). This transport acted to flush the Beaufort Sea of its first-year ice cover and fill it with MYI. Eight per cent of the Arctic’s MYI cover was transported into the Beaufort Sea in winter 2020/2021 (Fig. 2e), contributing to a record fraction of the MYI cover residing in the Beaufort Sea (23.5%) in the last full week of February (Fig. 2f). This fraction has been historically increasing over the data period (1983–2020), however, this high concentration is well above the linear trend (by 2.06 standard deviations; Figs. S9 and S10). Because around two-thirds of the Beaufort Sea has been ice-free on the first of September over the last decade (Fig.2h), this unprecedented concentration of Arctic MYI in the Beaufort Sea puts it at a larger risk of melting.”). 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.), 343 (“A reduction of survival rates of sea ice exported from the Siberian shelves by 15% per decade has interrupted the transpolar drift and affected the long-range transport of sea ice (Krupen et al., 2019). The thinner and on average younger ice has less resistance to dynamic forcing, resulting in a more dynamic ice cover (Hakkinen et al., 2008; Spreen et al., 2011; Vihma et al., 2012; Kwok et al., 2013).”).

119 Mallett, R. (10 August 2021) Record-breaking winter winds have blown old Arctic sea ice into the melt zone. ARCTIC TODAY (“In the Arctic, the breakdown of the polar vortex produced an exceptional pattern of surface winds that swirled clockwise about the center of the Arctic Ocean like water around a plughole. These swirling winds spun the floating icepack like a spinning top. In doing so, they drove the Arctic’s perennial ice from a relatively safe and cold position north of Greenland into an area where ice increasingly can’t survive the summer: the Beaufort Sea. Over the winter, the Beaufort Sea filled with perennial ice such that in the last week of February 2021, it contained a record fraction (23.5 percent) of the Arctic Ocean’s total perennial ice cover.”).
remained unclear. The results presented here show a more coherent cold season increase in
the Arctic coastline are warming at approximately twice the rate of sea
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e two decades. Such changes promote cyclone
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June has increased from the early to the recent decade by 67% more in the absence of cyclones than in the presence
contrast, June cyclones in both decades locally slow down seasonal sea

of the summer storm track to increasing land

was already thin on 4 August before the storm (Figures 1i and 2b)."

August

up to 0.5 m by 10 August (Figure 1l). The simulated ice in most of these areas

3d). The simulated total ice melt is 0.12 ×10
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Ice Loss from Late

Ice from Late

Sea Temperature

A Recent Climatology, J. GEOPHYS. RES. ATMOS. 126(12): 1–35, 20 (“One of the most intriguing results in our analysis of
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
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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 (“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.”); 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.: 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
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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.”).

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, 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 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.”). 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, 4, 6 (“In the high-emission scenario, five out of six selection criteria that include ocean heat transport provide a first ice-free Arctic in September before 2040 (range of multi-model means: 2032–2039), more than 20 years before the date of ice-free Arctic for the multi-model mean without model selection (i.e. 2061)”; “This model selection reveals that sea-ice area and volume reach lower values at the end of this century compared to the multi-model mean without selection. This arises both from a more rapid reduction in these quantities through this century and from a lower present-day sea-ice area. Using such a model selection, the timing of an almost ice-free Arctic in summer is advanced by up to 29 years in the high-emission scenario, i.e. it could occur as early as around 2035.”); 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?. Clim. Change 8(15): 1–24, 17 (“Excluding the values later than 2100, the averaged projected [first ice-free Arctic summer (FIASY)] value for RCP4.5 was 2054 with a spread of 74 years; for RCP8.5, the averaged FIASY was 2042 with a spread of 42 years. ...which put the mean FIASY at 2037. The RCP8.5 projections tended to push FIASY earlier, except for those of the MICRO-ESM and MICRO-ESM-CHEM models. Those two models also tended to project earlier Arctic ice-free dates and longer durations.”); Overland J. E. & Wang M. (2013) When will the summer Arctic be nearly sea ice free?. Geophys. Res. Lett. 40(10): 2097–2101, 2097 (“Three recent approaches to predictions in the scientific literature are as follows: (1) extrapolation of sea ice volume data, (2) assuming several more rapid loss events such as 2007 and 2012, and (3) climate model projections. Time horizons for a nearly sea ice-free summer for these three approaches are roughly 2020 or earlier, 2030 ± 10 years, and 2040 or later. Loss estimates from models are based on a subset of the most rapid ensemble members. … Observations and citations support the conclusion that most global climate model results in the CMIP5 archive are too conservative in their sea ice projections. Recent data and expert opinion should be considered in addition to model results to advance the very likely timing for future sea ice loss to the first half of the 21st century, with a possibility of major loss within a decade or two.”); Guarino M.-V., et al. (2020) Sea-ice-free Arctic during the Last Interglacial supports fast future loss. Nat. Clim. Change 10: 928–932, 931 (“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). More broadly, multimodel CMIP3–6 mean predictions (and ranges) for a summer sea-ice-free Arctic are as follows: CMIP3, 2062 (2040–2086); CMIP5, 2048 (2020–2081); and CMIP6, 2046 (2029–2066) (Fig. 4 and Supplementary Table 3). We note that the latest year of sea-ice disappearance for CMIP6 models is 2066 and that 50% of the models predict sea-ice-free conditions between ~2030 and 2040. From this we can see that HadGEM3 is not a particular outlier, in terms of its ECS or projected ice-free year.”); 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.), Figure SPM.8-b.

Sadatzki H., Maffezzoli N., Dokken T. M., Simon M. H., Berben S. M. P., Fahl K., Kjar H. A., Spolaor A., Stein R., Valdeleona 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 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 δ¹⁸O, recorded in MD99-2284 (Fig. 5). The increase in benthic δ¹⁸O 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).”

124 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 HadGEM3 model yields a much-improved representation of Arctic summers during the warmer LIG 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.”).

125 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).

126 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.”).

127 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/m² is approximately equivalent to the direct radiative effect of emitting one trillion tons of CO₂ into the atmosphere (see calculation in Appendix A). As of 2016, an estimated 2.4
trillion tons of CO₂ 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 CO₂ 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 CO₂ emissions at the current rate.”). See also Institute for Governance & Sustainable Development (2019) Plain Language Summary of Pistone K., et al.

128 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 CO₂ emissions is computed using the following approximate formula: \( f = (5.35 \text{ W/m}^2) \ln[xR] \) (Myhre et al., 1998). Here \( f \) is the radiative forcing relative to an arbitrary reference value \( R \), \( x \) is the atmospheric CO₂ concentration, and \( \ln \) indicates the natural logarithm. Note that this formula is an expression of the relationship that a doubling of atmospheric CO₂ causes a radiative forcing of 3.71 W/m². Considering a radiative forcing of 0.71 W/m², this translates to an increase in the atmospheric CO₂ concentration from 400 to 456.7 ppm. Since 1 ppm of atmospheric CO₂ 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 CO₂ (i.e., fraction of CO₂ 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 CO₂ enough to cause 0.71 W/m² of radiative forcing is 1.0 trillion tons (i.e., 441 Gt/0.44.”).

129 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/m² 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/m² (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 ºC (0.16–0.21 ºC) at a uniform background warming of 1.5 ºC (=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 0.43ºC (0.39–0.46 ºC). This effect is robust for a whole range of CO₂ emission scenarios up to 700 ppm and corresponds to 29% extra warming relative to a 1.5 ºC 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.

130 Forster P., Storelvmo T., Armour K., Collins W., Dufresne J.-L., Frame D., Lunt D. J., Mauritzen 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 CO₂ 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 CO₂ was 2.079 W/m² in 2019, 2.111 W/m² in 2020, and 2.140 W/m² in 2021.)

131 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/m² compared with the 1979 baseline state, which is 3 times more than the 0.71 W/m² baseline estimate derived above for unchanged clouds. The completely overcast ice-free Arctic scenario results in a global radiative heating of 0.37 W/m², which is approximately half as large as the 0.71 W/m² 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.”).
Fig. 3, B and C

ater infiltration, thawing and fires could, given the right set of circumstances, act together to expose and transfer permafrost C to the atmosphere very rapidly (Soja et al. 2004). See also McCarty J. L., Smith T. E. L., & Turetsky M. R. (2020) Extensive fires in southeastern Siberian permafrost linked to preceding Arctic Oscillation, Sci. Adv. 6(2): 1–7, 2, 4 ("Strictly speaking, the fire activity–related high-pressure pattern extends further into southeastern Siberia than the typical AO pattern. This suggests that the AO provides preferable conditions for strong fire activity (i.e., high-temperature anomalies), but the positive pressure anomaly extending westward from the North Pacific to southeastern Siberia explains more southeastern Siberian fire activity variability."); "In contrast, we found a significant negative relationship between March to April snow cover and total annual fire activity, as positive temperature anomalies related to a positive AO in February and March drive early snowmelt in March and April with a time lag of 1 to 2 months (Fig. 3, B and C, and fig. S6) (J8, 19). This is consistent with results from a snow water equivalent dataset (fig. S7). 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 (J22).… This analysis shows a generally negative relation between burned area and P/PET, meaning that more arid regions have stronger fire activity."); and Environmental Protection Agency (2012) Report to Congress on Black Carbon, EPA-450/R-12-001.

132 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 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., & Schaeppan-Strub G. (2020) Extensive fires in southeastern Siberian permafrost linked to preceding Arctic Oscillation, Sci. Adv. 6(2): 1–7, 2, 4 ("Strictly speaking, the fire activity–related high-pressure pattern extends further into southeastern Siberia than the typical AO pattern. This suggests that the AO provides preferable conditions for strong fire activity (i.e., high-temperature anomalies), but the positive pressure anomaly extending westward from the North Pacific to southeastern Siberia explains more southeastern Siberian fire activity variability."); “In contrast, we found a significant negative relationship between March to April snow cover and total annual fire activity, as positive temperature anomalies related to a positive AO in February and March drive early snowmelt in March and April with a time lag of 1 to 2 months (Fig. 3, B and C, and fig. S6) (J8, 19). This is consistent with results from a snow water equivalent dataset (fig. S7). 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 (J22)…. This analysis shows a generally negative relation between burned area and P/PET, meaning that more arid regions have stronger fire activity."); and Environmental Protection Agency (2012) Report to Congress on Black Carbon, EPA-450/R-12-001.

133 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’, 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 and burning can accelerate thaw and carbon emission rates").

134 Sharma M., Dickie G., Arranz A., & Scarr S. (8 September 2022) Why Arctic wildfires are releasing more carbon than ever, REUTERS ("Arctic wildfires that sparked above the 66th parallel unleashed an estimated 16 million tonnes of carbon in 2021 — roughly equal to the annual carbon dioxide (CO2) emissions of Peru — according to a report by the Copernicus Climate Change Service.").

135 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.").

73
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. 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 $570 \pm 480\%$ 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. The loss of this layer through wildfire combustion will expose the underlying permafrost to substantial warming and degradation and lead to thermokarst development in ice-rich permafrost60. … 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. … 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.”). See also Witze A. (10 September 2020) The Arctic is burning like never before — and that’s bad news for climate change, Nature News (“Wildfires blazed along the Arctic Circle this summer, incinerating tundra, blanketing Siberian cities in smoke and capping the second extraordinary fire season in a row. By the time the fire season waned at the end of last month, the blazes had emitted a record 244 megatonnes of carbon dioxide — that’s 35% more than last year, which also set records. One culprit, scientists say, could be peatlands that are burning as the top of the world melts.”).

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 smoldering 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 smoldering phase and may burn deeper than our emissions model currently predicts. In addition, smoldering fires emit relatively more methane and less carbon dioxide in comparison to flaming fires, yet methane has a much larger global warming potential.”).

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 difference 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
Permafrost emissions, 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 CO₂) 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

143 Annual U.S. CO₂ emissions from Figure 1 in U.S. EPA Climate Change Indicators: U.S. Greenhouse Gas Emissions (last visited 13 June 2023).

144 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, 20 (“Today permafrost covers ~23 million km²of the planet, with 13–18 × 10⁹ km² in the Arctic, 1.06 × 10⁹ km² in the Tibetan plateau and 16–21 × 10⁹ km² 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”). Rapid anthropogenic warming and resultant thaw threaten to mobilize permafrost carbon stores3,4, potentially increasing atmospheric concentrations of carbon dioxide (CO₂) and methane (CH₄), 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.

145 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(085003): 1–9, 2 (“If temperatures rise and permafrost thaws, the organic material will also thaw and begin to decay, releasing carbon dioxide (CO₂) and methane (CH₄) into the atmosphere and amplifying the warming due to anthropogenic greenhouse gas emissions … The PCF 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 CO₂ 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, 166 (“The permafrost carbon feedback (PCF) is an amplification of surface warming due to the release into the atmosphere of carbon currently frozen in permafrost (Fig. 1). As atmospheric CO₂ and methane concentrations increase, surface air temperatures will increase, causing permafrost degradation and thawing some portion of the permafrost carbon. Once permafrost carbon thaws, microbial decay will resume, increasing respiration fluxes to the atmosphere and atmospheric concentrations of CO₂ and methane. This will in turn amplify the rate of atmospheric warming and accelerate permafrost degradation, resulting in a positive PCF feedback loop on climate (Zimov et al., 2006b.”); and Chen Y., Liu A., & Moore J.C. (2020) Mitigation of Arctic permafrost carbon loss through stratospheric aerosol geoengineering, NAT. COMMUN. 11(2430): 1–35, 2, 3 (“Between 2020 and 2069, Plnc-Panther simulations of soil C change, driven by outputs of 7 ESMs for the RCP4.5 projection, varied from 19.4 Pg C gain to 52.7 Pg C loss (mean 25.6 Pg C loss), while under G4 the ensemble mean was 11.9 Pg C loss (range: 29.2 Pg C gain to 44.9 Pg C loss). Projected C losses are roughly linearly proportional to changes in soil temperature, and each 1 °C warming in the Arctic permafrost would result in ~13.7 Pg C loss; the y-intercept indicates that the Arctic permafrost, if maintained in current state, would remain a weak carbon sink. MIROC-ESM and MIROC-ESM-CHEM, with simulations of warming above 3°C, produce severe soil C losses, while GISS-E2-R with minor soil temperature change produces net soil C gains under both scenarios before 2070.”); “PlncPanTher simulations of the anoxic respiration rates over the period 2006–2010 are 1.2–1.7 Pg C year⁻¹, and so the estimated range of CH₄
emissions is 28–39 Tg year\(^{-1}\), which is very close to the 15–40 Tg CH\(_4\) year\(^{-1}\) estimates of current permafrost wetland CH\(_4\) emissions.”).

146 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\(_2\)O), 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\(_2\)O 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\(_2\)O 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\(_2\)O 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\(_2\)O 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\(_2\)O), 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").

147 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% [of 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).

148 Smith S. L., O’Neill H. B., Isaksen K., Noetlitz 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., Trevin 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).”\textsuperscript{149}

Note that PgC\textsubscript{eq} for the methane feedback is converted to GtCO\textsubscript{2}-eq 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 (“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\textsubscript{2} feedback per degree of global warming (Figure 5.29) is 18 (3.1–41, 5th–95th percentile range) PgC °C\textsuperscript{−1}. The assessment is based on a wide range of scenarios evaluated at 2100, and an assessed estimate of the permafrost CH\textsubscript{4}-climate feedback at 2.8 (0.7–7.3 5th–95th percentile range) Pg C\textsubscript{eq} °C\textsuperscript{−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\textsubscript{2} in the period from 2100 to 2300 under a RCP2.6 scenario, and 115–172 PgC of CO\textsubscript{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\textsubscript{4} over the 21st century and 2800–7400 Tg CH\textsubscript{4} from 2100–2300 (Schneider von Deimling et al., 2015), and as 5300 Tg CH\textsubscript{4} over the 21st century and 16000 Tg CH\textsubscript{4} from 2100–2300 (Turetsky et al., 2020). For RCP4.5, these numbers are 538–2356 Tg CH\textsubscript{4} until 2100 and 2000–6100 Tg CH\textsubscript{4} from 2100–2300 (Schneider von Deimling et al., 2015), and 4100 Tg CH\textsubscript{4} until 2100 and 10000 Tg CH\textsubscript{4} from 2100–2300 (Turetsky et al., 2020).”\textsuperscript{149} 739 (“Other feedback contributions, such as the non-CO\textsubscript{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\textsubscript{2} biogeochemical feedbacks combine to a linear feedback term of 30 ± 27 PgC\textsubscript{eq} °C\textsuperscript{−1} (1 standard deviation range, 111 ± 98 Gt CO\textsubscript{2}-eq °C\textsuperscript{−1}), including a feedback term of −11 [−18 to −5] PgC\textsubscript{eq} °C\textsuperscript{−1} (5–95% range, −40 [−62 to −18] Gt CO\textsubscript{2}-eq °C\textsuperscript{−1}) from natural CH\textsubscript{4} and N\textsubscript{2}O sources. The biogeochemical feedback from permafrost thaw leads to a combined linear feedback term of −21 ± 12 PgC\textsubscript{eq} °C\textsuperscript{−1} (1 standard deviation range −77 ± 44 Gt CO\textsubscript{2}-eq °C\textsuperscript{−1}).”\textsuperscript{149} 737 (“Land biosphere models show high agreement that long-term warming will increase N\textsubscript{2}O release from terrestrial ecosystems (Xu et al., 2012; B.D. Stocker et al., 2013; Zaele, 2013; Tian et al., 2019). A positive land N\textsubscript{2}O 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\textsubscript{2}O emissions to atmospheric CO\textsubscript{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\textsubscript{2}O climate feedback is positive, but low confidence in the magnitude (0.02 ± 0.01 W m\textsuperscript{−2} °C\textsuperscript{−1}).”\textsuperscript{149}

\textsuperscript{150} Hunt K. (14 March 2022) Holes in the size of city blocks are forming in the Arctic seabed, CNN (“Marine scientists have discovered deep sinkholes – one larger than a city block of six-story buildings – and ice-filled hills that have formed “extraordinarily” rapidly on a remote part of the Arctic seabed.”). \textsuperscript{150}

\textsuperscript{151} 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\textsubscript{4} (Mt C) and 10.95 Gt CO\textsubscript{2} (Gt C) under the worst-case RCP8.5 scenario (Turetsky et al., 2020).”\textsuperscript{151} 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
Carbon release through abrupt permafrost thaw, Nat. Geosci. 13(2): 138–143, 138–139 ("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 CH₄ (Mt C) and 10.95 Gt CO₂ (Gt C) under the worst-case RCP8.5 scenario (Turetsky et al., 2020)."")

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 km² of abrupt thaw could provide a similar climate feedback as gradual thaw emissions from the entire 18 million km² 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 CH₄, 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 CH₄, 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 permafrost 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).”

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.”).

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 CH4 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 CH4 emissions. Each crater does not contain exceptional levels of CH4, 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 6°C 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.

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,
The frequency of boreal forest fires is projected to increase even more with expected climate warming and drying and, as a result, the total burned area is expected to increase to 130%–350% by mid-century. 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.

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, PROG. 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)”).

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. Alarming, these figures are not reduced substantially even if the climate change targets of the Paris Agreement are reached.”).

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.”).

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., Trulb G., Tañ 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.

160 See Wadham 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 (Shakova 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).”

161 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 CH₄ and CO₂ concentrations. Taking age model uncertainties into consideration, during the peak in anomalously low carbon isotopes, the atmospheric CO₂ and CH₄ 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 δ¹³C values of atmospheric CO₂ declined by 0.3 to 0.4‰ coeval with the δ¹³C anomaly recorded in the Gulf of Guinea sediment sequence (SI Appendix, Fig. S9) (50, 52), indicating that a source with a significantly negative δ¹³C signature contributed to the increase of atmospheric CO₂. 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.”).

162 Whiteman G., Hope C., & Wadham 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 Wadham 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.

163 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).”).

164 Ye W., Li Y., Wen J., Zhang J., Shakohva 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 CH₄ was significantly enhanced in the Chukchi Sea and distributed northward with the shelf-break jet, providing clear evidence of increased CH₄ transport from the Chukchi Sea shelf to the central Arctic in the 2010s compared with the 1990s.”).

165 Wadham J. L., Hawkins 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 CH₄ 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 CH₄ 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 Dessardier 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 δ¹³C. This is quickly followed by the precipitation of methane-derived authigenic carbonate as overgrowth inside and outside foraminiferal shells, characterized by heavy δ¹⁸O and depleted δ¹³C 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.”).  

166 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 Ørjan 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.

167 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 CH₄ production by subsea permafrost decomposition estimated here, and the likely oxidation of part of this CH₄, 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 CH₄ production rates, and the limitations of upscaling from incubations to natural environments. Taken together, the high CH₄ emissions ubiquitously observed in the field likely stem from other sources such as preformed CH₄ in gas pockets in the subsea permafrost, collapsing CH₄ hydrates, or venting of a deep thermogenic CH₄ pool.”).

168 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 CH₄ emissions from old permafrost carbon range from 0 to 53 Tg CH₄ per year (table S10) throughout the last deglaciation and may have contributed up to 27% of the total CH₄ 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 CH₄ emissions from old carbon reservoirs, such CH₄ 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 TgCH₄ 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; Dyoniussi et al., 2020). The long timescales associated with clathrate destabilisation makes it unlikely that CH₄ 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).

169 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).”). See also 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, 75 (“Current policies and actions make it very likely, at least temporarily, to overshoot the Paris climate targets of 1.5–2.0 °C above pre-industrial levels. If this global warming range is exceeded, potential tipping elements such as the Greenland Ice Sheet and Amazon rainforest may be at increasing risk of crossing critical thresholds. This raises the question of how much this risk is amplified by increasing overshoot magnitude and duration. Here we investigate the danger for tipping under a range of temperature overshoot scenarios using a stylized network model of four interacting climate tipping elements. Our model analysis reveals that temporary overshoots can increase tipping risks by up to 72% compared with non-overshoot scenarios, even when the long-term equilibrium temperature stabilizes within the Paris range. Our results suggest that avoiding high-end climate risks is possible only for low-temperature overshoots and if long-term temperatures stabilize at or below today’s levels of global warming.”); 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).”).

170 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 CO₂ 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 Pattyn F., et al. (2018) The Greenland and Antarctic ice sheets under 1.5 °C global warming, Nat. Clim. Change 8(12): 1053–1061, 1053 (“On millennial timescales, both ice sheets have tipping points at or slightly above the 1.5–2.0 °C threshold; for Greenland, this may lead to irreversible mass loss due to the surface mass balance–elevation feedback, whereas for Antarctica, this could result in a collapse of major drainage basins due to ice-shelf weakening.”).
Ice mass (figure 2f, 2g). In 2020, the minimum summer Arctic sea ice was at its second smallest extent on record, and glacier thickness also set a new all-time low (figure 2e, 2h). Glaciers are melting much faster than previously believed; they are losing 31% more snow and ice per year than they did just 15 years ago (Hugonnet et al. 2021).

Turner J., Holmes C., Caton Harrison T., Phillips T., Jena B., Reeves-Francois T., Fogt R., Thomas E. R., & Bajish C. C. (2022) Record Low Antarctic Sea Ice Cover in February 2022. Geophys. Res. Lett. 49(12): 1–11, 1 (“On 25 February 2022 Antarctic sea ice extent dropped to a satellite-era record low level of $1.92 \times 10^6$ km$^2$, $0.92 \times 10^6$ km$^2$ below the long-term mean. The area of sea ice was also at a record low level of $1.24 \times 10^6$ km$^2$.”).

Box J. E., Hubbard A., Bahr D. B., Colgan W. T., Fettweis X., Mankoff K. D., Wehrle A., Noël B., van den Broeke M. R., Wouters B., Björk 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$_0$ ($a$) disequilibrium with the current ice configuration corresponding with a $3.3 \pm 0.8\%$ 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 $274 \pm 68$ mm of global eustatic SLR.”; “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 $274 \pm 68$ 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.

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 satellites]. 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 Antarctica 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.”); summarizing 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.

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
Recent studies have focused on the short.

...eshold alone does not,
d lead to GMSL rise well above the
... (low confidence).”). See also Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetyski 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 (Tirisos et al., 2022). Over longer timescales, sustained high rates of global sea-level rise (>1 cm/yr by 2200, with further acceleration to up to a couple centimeters per year beyond) may broadly strain coastal adaptation efforts (Oppenheimer et al., 2019). At the same time, models indicate that strong climate mitigation may avert significant fractions of potential sea-level rise and prevent ice-sheet collapse across large regions. In several modeling studies the RCP2.6 scenario prevents collapse of the WAIS (Bulthuis et al., 2019; DeConto & Pollard, 2016) and may reduce the Antarctic contribution to global sea level rise by 2100 to 13 cm (Edwards et al., 2021).... 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).”

177 Boers N. & Rypdal M. (2021) Critical slowing down suggests that the western Greenland Ice Sheet is close to a tipping point, PROC. NAT’L. ACADEM. 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., Úrge-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).”).

178 Robinson A., Calov R., & Ganopoliski 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 °C (1.9–5.1 °C, 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 °C, with a best estimate of 1.6 °C. 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.”). See also 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.”); Schleussner C.-F., Lissner T. K., Fischer E. M., Wohland J., Perrette M., Golly A., Rogel J., Childers K., Schewe J., Frieler K., Menge M., Hare W., & Schaeffer M. (2016) Differential Climate Impacts for Policy-Relevant Limits to Global Warming: the Case of 1.5°C and 2°C, EARTH SYST. DYNAM. 7(2): 327–351, 342 (“In addition to that, Levermann et al. (2013) report a steep increase in long-term SLR between 1.5°C and 2°C as a result of an increasing risk of crossing a destabilizing threshold for the Greenland ice-sheet (Robinson et al., 2012). The disintegration process that would lead to 5–7m global SLR, however, is projected to happen on the timescale of several millennia.”); and Kopp R. E., Shwon R. L., Wagner G., & Yuan J. (2016) Tipping elements and climate–economic shocks: Pathways toward integrated assessment, EARTH’S FUTURE 4(8): 346–372, 354–355 (“For the Greenland Ice Sheet, for example, feedbacks between ice sheet topography and atmospheric dynamics and between ice area and albedo give rise to multiple stable states [Ridley et al., 2009; Robinson et al., 2012; Levermann et al., 2013]. Robinson et al. [2012]’s coupled ice-sheet/regional climate model indicated that, at a temperature of 1°C above pre-Industrial temperatures, the stable states are at 100%, 60%, and 20% of present ice volume. At 1.6°C, however, their model produced only one stable configuration, at ~15% of the Greenland ice sheet’s present volume; thus, 1.6°C warming would represent a commitment to ~6 m of sea-level rise from the Greenland Ice Sheet. The rate of ice sheet mass loss is, however, limited by the flux at the ice sheet margins [e.g., Pfeffer et al., 2008], leading to a disconnect between committed and realized change that could persist for millennia, particularly for levels of warming near the threshold [Applegate et al., 2015].”). If warming is limited to 2 °C, Greenland could contribute 5 cm of sea-level rise by 2050 and 13 cm by 2100, but if emissions are unabated and warming rises to 5 °C, Greenland could contribute 6 cm of sea-level rise by 2050 and 23 cm by 2100: see Bamber J. L., Oppenheimer M., Kopp R. E., Aspinall W. P., & Cooke R. M. (2019) Ice sheet contributions to future sea-level rise from structured expert judgment, PROC. NAT’L. ACAD. SCI. 116(23): 11195–11200, 11197 (Table 1).

179 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.”).

180 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. Here we combine more than three decades of remotely sensed observational products of outlet glacier velocity, elevation, and front position changes over the full ice sheet. We compare decadal variability in discharge and calving front position and find that increased glacier discharge was due almost entirely to the retreat of glacier fronts, rather than inland ice sheet processes, with a remarkably consistent speedup of 4–5% per km of retreat across the ice sheet. We show that widespread retreat between 2000 and 2005 resulted in a step-increase in discharge and a switch to a new dynamic state of sustained mass loss that would persist even under a decline in surface melt.”). When compared to the projections of the IPCC Fifth Assessment Report, the associated sea-level rise from the recent ice sheet melting of both Greenland and Antarctica is most like the upper range projections: see Slater T., Hogg A. E., & Mottram R. (2020) Ice-sheet losses track high-end sea-level rise projections, Comment, NAT. CLIM. CHANGE 10: 879–881, 881 (“In AR5, the ice-sheet contribution
by 2100 is forecast from process-based models simulating changes in ice flow and surface mass balance (SMB) in response to climate warming. Driven by the century-scale increase in temperature forced by representative concentration pathways (RCPs), global mean SLR estimates range from 280–980 mm by 2100 (Fig. 1). Of this, the ice-sheet contribution constitutes 4–420 mm (ref. 3). The spread of these scenarios is uncertain, scenario-dependent and increases rapidly after 2030 (Fig. 1). During 2007–2017, satellite observations show total ice-sheet losses increased the global sea level by 12.3 ± 2.3 mm and track closest to the AR5 upper range (13.7–14.1 mm for all emissions pathways) (Fig. 1). Despite a reduction in ice-sheet losses during 2013–2017 — when atmospheric circulation above Greenland promoted cooler summer conditions and heavy winter snowfall2 — the observed average SLR rate (1.23 ± 0.24 mm per year) is 45% above central predictions (0.85 ± 0.07 mm per year) and closest to the upper range (1.39 ± 0.14 mm per year) (Fig. 2)."

In mid-September 2020, consistent warming over northeast Greenland contributed to a large chunk of a glacier breaking away from the Arctic’s largest remaining ice shelf: see Amos J. (14 September 2020) Climate change: Warmth shatters section of Greenland ice shelf, BBC News (“A big chunk of ice has broken away from the Arctic’s largest remaining ice shelf - 79N, or Nioghalvfjerdsfjorden - in northeast Greenland. The ejected section covers about 110 square km; satellite imagery shows it to have shattered into many small pieces. The loss is further evidence say scientists of the rapid climate changes taking place in Greenland. … At its leading edge, the 79N glacier splits in two, with a minor offshoot turning directly north. It’s this offshoot, or tributary, called Spalte Glacier, that has now disintegrated. The ice feature was already heavily fractured in 2019; this summer’s warmth has been its final undoing. Spalte Glacier has become a flotilla of icebergs.”).

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.”).

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.”).

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.”).

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., Bjerk A. A., & Fausto R. S. (2022) Greenland ice sheet climate disequilibrium and committed sea-level rise, Nat. Clim. Change: 808–816, 808 (“Ice loss from the Greenland ice sheet is one of the largest sources of contemporary sea-level rise (SLR). While process-based models place timescales on Greenland’s deglaciation, their confidence is obscured by model shortcomings including imprecise atmospheric and oceanic couplings. Here, we present a complementary approach resolving ice sheet disequilibrium with climate constrained by satellite-derived bare-ice extent, tidewater sector ice flow discharge and surface mass balance data. We find that Greenland ice
imbalance with the recent (2000–2019) climate commits at least 274 ± 68 mm [10.8 ± 2.7 in] SLR from 59 ± 15 × 103 km² ice retreat, equivalent to 3.3 ± 0.9% volume loss, regardless of twenty-first-century climate pathways. This is a result of increasing mass turnover from precipitation, ice flow discharge and meltwater run-off. The high-melt year of 2012 applied in perpetuity yields an ice loss commitment of 782 ± 135 mm [30.8 ± 5.3 in] SLR, serving as an ominous prognosis for Greenland’s trajectory through a twenty-first century of warming.”); 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.

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.”).

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-flopping 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). Høegh-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. A recent paper suggests that even small, incremental changes in freshwater forcing could drive AMOC collapse if the rate of forcing is sufficiently rapid (Lohmann & Ditlevsen, 2021). However, the current ability of models to accurately represent the AMOC and predict its response to climate change remains low, leaving the proximity of today’s AMOC to potential critical thresholds uncertain (Weijer et al., 2019).”); “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.”); 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.”); and Ritchie P. D. L., Clarke J. J., Cox P. M., & Huntingford C. (2021) Overshooting tipping point thresholds in a changing climate, Nature 592(7855): 517–523, 522 (“Our analysis reveals that for many climate tipping points it is possible to cross a threshold temporarily without triggering tipping to a different system state. This finding is particularly relevant for potential slow-onset tipping elements such as ice-sheet melt or collapse of the AMOC. Hence, the point of no return...
for a slow-onset tipping element is not the threshold but some point beyond the threshold. How far this point is beyond the threshold is determined by three factors: (1) the effective timescale of the system, (2) how fast global warming can be reduced and (3) the level at which warming stabilizes.”).

187 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 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 Dittevens, 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.”).

188 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 CO2 doubling approximately between the RCP4.5 and RCP6.0 scenarios produced an AMOC collapse 300 years after the CO2 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.”).

189 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.”).

190 Sweet W. V., et al. (2022) *GLOBAL AND REGIONAL SEA LEVEL RISE SCENARIOS FOR THE UNITED STATES: UPDATED MEAN PROJECTIONS AND EXTREME WATER LEVEL PROBABILITIES ALONG U.S. COASTLINES*, National Oceanic and Atmospheric Administration Technical Report NOS 01, 40 (“By 2050, moderate HTF frequencies nationally are projected to increase by more than a factor of 10, with about a factor of 5 increase in major HTF frequencies. In short, assuming continuation of current trends and summarized at the national level, a flood regime shift is projected by 2050, with moderate HTF occurring a bit more frequently than minor HTF events occur today and major HTF events occurring about as frequently as moderate HTF frequencies occur today”).

191 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., Úrge-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 latitudinal 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 redistribution 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 northern 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.”).

192 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 (“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 transport50, 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.”); 847 (“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.”).

193 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).

194 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.

195 Graham A. G. C., Wählín 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., & Larer 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 seafloor 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
hwaites' Eastern Ice Shelf would be held in place by an underwater mountain. The ice shelf acts like a brace that prevents becoming rapidly destabilized. The eastern winds and positive feedbacks from the ungrounding of ice sheets (P. R. Holland et al., 2019) forced shifts in regional climate systems and enhances according to Erin Pettit, a professor at Oregon State University. Beneath the surface, warmer ocean water circulating beneath the floating eastern side is attacking this glacier from all angles, her team has found. This water is melting the ice directly from beneath, priming the ice shelf for disintegration. 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. 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. The observational record has established the predominant role of ocean warming in combination with physical stresses can also drive a fast flow of the upstream ice. But the brace of ice slowing Thwaites won’t last for long, said Erin Petitt, an associate professor at Oregon State University. Beneath the surface, warmer ocean water circulating beneath the floating eastern side is attacking this glacier from all angles, her team has found. This water is melting the ice directly from beneath, and as it does so, the glacier loses its grip on the underwater mountain. Massive fractures 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.”).
Elevated ocean temperatures since the 1970s imply a long-term transfer of energy to the ocean, with land warming, ice loss and atmospheric warming accounting for about 5%, 3% and 1%, respectively (high confidence). As radiative forcing decays further, the energy will ultimately be restored to the ocean and atmosphere. However, the energy is still available to be transferred back to the atmosphere for centuries following cessation of emissions, which 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 (high confidence).

See also MacDougall A. H., et al. (2020) Is there warming in the pipeline? A multi-model analysis of the Zero Emissions Commitment from CO₂ emissions. Biotic, 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 SYNTHESES 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., Úrge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 42 (“Sea level rise is unavoidable for centuries due to continuing deep ocean warming and ice sheet melt, and sea levels will remain elevated for thousands of years (high confidence).”)

See also Cheng L., Abraham J., Hausfather Z., Trenberth K. E., & Abraham J. (2022) Improved Quantification of the Rate of Ocean Warming, J. Clim. 35(14): 4827–4840, 4838 (A robust increase of ocean warming for the upper 2000 m has occurred since 1958 from about 0 to 0.06 ± 0.08 W m⁻² for 1958–73 to 0.58 ± 0.08 W m⁻² in 2003–18. With the new methods, the rates of OHC change and EEI since 1958 have been recalculated and updated. The total ocean warming for the upper 2000 m is 341.3 ± 21.0 ZJ from 1958 to 2020 (with the 95% confidence interval). The new estimate suggests a dramatic increase of ocean heat uptake and EEI from 1980s to early 2000s. For the most recent period with better data quality (2005–19) and another estimate of land–ice–atmosphere heat content (Trenberth 2022), the EEI is estimated to 153.9 ZJ (10.99 ZJ yr⁻¹) with the ocean heat uptake of 139.7 ZJ (9.98 ZJ yr⁻¹) for 2005–19. This estimate
is slightly lower than that using von Schuckmann et al. (2020) in Fig. 8, indicating uncertainty in land–ice–atmosphere heat content.”

202 Cheng L., et al. (2023) Another Year of Record Heat for the Oceans, ADV. ATMOS. SCI. 40: 963–974, 972 (“First, we find that the oceans are continuing to warm globally, with yet another new 0–2000 m OHC record reached in 2022. The inexorable climb in ocean temperatures is the inevitable outcome of Earth’s energy imbalance, primarily associated with increasing concentrations of greenhouse gases. The global long-term warming trend is so steady and robust that annual records continue to be set with each new year. The warming has accelerated in recent decades, with a faster rate of warming evident since roughly 1990 (Cheng et al., 2022a, b). Similarly, the SC index has increased, signifying more extreme salinity anomalies and an imprint of global water cycle amplification on the upper ocean. We also show a sustained increase in ocean stratification, with ocean waters becoming increasingly more stable over time, although with more variability than other fields.”; discussed in Berwyn B. (11 January 2023) Relentless Rise of Ocean Heat Content Drives Deadly Extremes. INSIDE CLIMATE NEWS.

203 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 CO₂ 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).”).

204 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 N₂O slows the rate of warming a decade or two earlier than decarbonization alone and avoids the 2°C threshold altogether. These non-CO₂ 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 Khoudrajie 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 CH₄ and BC mitigation would contribute to offsetting the additional warming associated with SO₂ 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 CO₂ 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),” and 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 CO2 emissions, as for the CO2-measures scenario, does little to mitigate warming until after the next 20-30 years (Box 6.2). In fact, sulphur dioxide (SO2) is co-emitted with CO2 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 CO2-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 CO2 emissions in the past. The CO2-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 CH4 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 CO2 measures, so that the emissions reductions of the short-lived pollutants are almost identical regardless of whether the CO2 measures are implemented or not, as shown in Chapter 5. The near-term measures and the CO2 measures also impact climate change over different timescales owing to the different lifetimes of these substances. In essence, the near-term CH4 and BC measures are effectively uncoupled from CO2 measures examined here.”).

***Climate scientist and IPCC author Joeri Rogelj, as quoted in 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 CO2, 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.”).
Eowering, in particular over the major aerosol emission regions. This shows how cleaning up aerosols, predominantly sulfate, may add an additional half a degree of global warming, with impacts that strengthen 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°C of global warming, we need massive reductions of greenhouse gas emissions, per degree of surface warming, in particular over the major aerosol emission regions. … “

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 gl

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 column 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-quarters of the CO₂ induced radiative forcing of 1.8 W m⁻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, 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 circulation³⁴,⁴⁰, and precipitation over SA, and likely also for East Asia and all tropical regions.”).

209 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 CO₂ 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).”).

210 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, Supplemental Information, 7 (Table S1. The contribution of individual mitigation measures to the warming in the 21st century.).

211 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, 10320, Table S1 (“Hence, the CO₂ measures implemented in 2020 will unmask some of the aerosol cooling (red lines in SI Appendix, Fig. S5) and offset the warming reduction by CO₂ and SLCP mitigation. In the baseline scenarios of this study, the cooling aerosols are regulated gradually between 2020 and 2100 (SI Appendix, Fig. S6), whereas in the mitigation scenario examined here, CO₂ mitigation is implemented starting from 2020 and CO₂ emission is brought to net zero in about three decades (SI Appendix, Fig. S2B). As a result, the unmasking of coemitted aerosol cooling (a net warming effect) is more rapid in the decreasing CO₂ emissions beginning in 2020 (CN2020) mitigation scenario (SI Appendix, Fig. S5B vs. S7).”; Table S1 [graph depicting warming potential based on cumulative emissions from CO₂ only, aerosols only, and short-lived climate pollutants only from the 1970’s into the 2090’s]). See also Xu Y. (2020, personal communication). The baseline-fast warming scenario against which these mitigation scenarios are compared includes “unmasking” as emissions of cooling aerosols are reduced in the baseline-fast (RCP6.0) scenarios. If these aerosol emissions continued at current emission levels, undesired from air quality perspective, the warming in 2100 would be 0.6°C smaller.

212 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, Supplemental Information, 1 (“In the Baseline-default scenario for CO₂, the emission keeps increasing throughout the 21st century (RCP8.5). The 5% to 95% range of baseline-default is also adopted (Fig. S1b). In the baseline-fast scenario for CO₂ (pre-INDCs), emissions effectively increase at a rate of 1.1%/year before 2030 and then following Representative Concentration Pathway 6.0 (Fig. S1a). In the mitigation scenario for CO₂ (i.e. INDCs and post-2030 decarbonization), emissions effectively increase at a rate of 0.8%/year before 2030 (following INDCs) and then decrease at a rate of 5.5%/year after 2030 (CN2030 in Fig. S2a).”).

213 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, Supplemental Information, 1 (“In the Baseline-default scenario for CO₂, the emission keeps increasing throughout the 21st century (RCP8.5). The 5% to 95% range of baseline-default is also adopted (Fig. S1b). In the baseline-fast scenario for CO₂ (pre-INDCs), emissions effectively increase at a rate of 1.1%/year before 2030 and then following Representative Concentration Pathway 6.0 (Fig. S1a). In the mitigation scenario for CO₂ (i.e. INDCs and post-2030 decarbonization), emissions effectively increase at a rate of 0.8%/year before 2030 (following INDCs) and then decrease at a rate of 5.5%/year after 2030 (CN2030 in Fig. S2a). The CN2020 scenario is the same as CN2030, except that the peak of emission is reached at 2020 (Fig. S2b).”). See also Id. Supplemental Information, 7 (Table S1. The contribution of individual mitigation measures to the warming in the 21st century.).
...
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).”

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 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.”).

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 CO₂ 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 CH₄, BC, HFC, and N₂O (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-CO₂ measures is 0.26°C, almost 4 times larger than the net benefit of decarbonization alone (0.07°C) (Table S5).”).

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 (“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 Szopa S., Naik V., Adhikary B., Artaxo P., Berntsen T., Collins W. D., Fuzzi S., Gallardo L., Kiemler-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 CH₄, 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).”).
...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)."

See also 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 CO₂ emissions, as for the CO₂-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 °C (range 0.2 to 1.3 °C) at 2040. This is a large portion of the 1.1 °C (range 0.7 to 1.7 °C) 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.").

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 CO₂ emissions are reduced compared to modelled 2019 emissions by 27% [11–46%] in 2030 and by 52% [36–70%] in 2040; and global CH₄ 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 CO₂ emissions are reduced compared to modelled 2019 emissions by 48% [36–69%] in 2030 and by 80% [61–109%] in 2040; and global CH₄ emissions are reduced by 34% [21–57%] in 2030 and 44% [31–63%] in 2040. There are similar reductions of non-CO₂ emissions by 2050 in both types of pathways: CH₄ is reduced by 45% [25–70%]; N₂O 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 CH₄ 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 CH₄ could further reduce peak warming. (high confidence) (Figure SPM.5.").

Allen M. R., Dube O. P., Solecki W., Aragón-Durand F., Cramer W., Humphreys S., Kainuma M., Kala J., Mahowald N., Mulugetta Y., Perez R., Wairiu M., & Zickfeld K. (2018) *Chapter 1: Framing and Context*, in *Global Warming of 1.5 °C*, Special Report of the Intergovernmental Panel on Climate Change, Masson-Delmotte V., et al. (eds.), 61 ("If emission reductions do not begin until temperatures are close to the proposed limit, pathways remaining below 1.5°C necessarily involve much faster rates of net CO₂ emission reductions (Figure 1.4, green lines), combined with rapid reductions in non-CO₂ forcing and these pathways also reach 1.5°C earlier. Note that the emissions associated with these schematic temperature pathways may not correspond to feasible emission scenarios, but they do illustrate the fact that the timing of net zero emissions does not in itself determine peak warming: what matters is total cumulative emissions up to that time. Hence every year’s delay before initiating emission reductions decreases by approximately two years the remaining time available to reach zero emissions on a pathway still remaining below 1.5°C (Allen and Stocker, 2013; Leach et al., 2018."). See also United Nations Environment Programme & Climate

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220 Shindell D., et al. (2012) *Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security*, SCIENCE 335(6065): 183–189, 183–185 ("The global mean response to the CH₄ plus BC measures was –0.54 ± 0.05°C in the climate model. Roughly half the forcing is relatively evenly distributed (from the CH₄ 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.").

221 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 CO₂ emissions are reduced compared to modelled 2019 emissions by 27% [11–46%] in 2030 and by 52% [36–70%] in 2040; and global CH₄ 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 CO₂ emissions are reduced compared to modelled 2019 emissions by 48% [36–69%] in 2030 and by 80% [61–109%] in 2040; and global CH₄ emissions are reduced by 34% [21–57%] in 2030 and 44% [31–63%] in 2040. There are similar reductions of non-CO₂ emissions by 2050 in both types of pathways: CH₄ is reduced by 45% [25–70%]; N₂O 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 CH₄ 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 CH₄ could further reduce peak warming. (high confidence) (Figure SPM.5.").
& Clean Air Coalition (2021) Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions, 20 (“For the 2015 United Nations (UN) Paris Agreement to succeed, reducing anthropogenic methane in addition to carbon dioxide is paramount. Currently the largest contributor to the departure from an idealized path to the 2°C target used in the IPCC’s Fifth Assessment Report is the growth in methane amounts (Figure 1.3). Achieving the more stringent 1.5°C target requires even larger decreases in methane. The IPCC’s 2018 Special Report concluded that reaching a sustainable mitigation pathway to 1.5°C can only be achieved with deep and simultaneous reductions of carbon dioxide and all non-carbon dioxide climate forcing emissions, including short-lived climate pollutants such as methane.”).


225 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).”).

226 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 stocktakesof progress towards achieving any multi-decade-timescale global temperature goal. In addition to specifying targets for total CO2-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 CO2 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) to provide ‘information necessary for clarity, transparency and understanding’ in nationally determined contributions (NDCs) and long-term low-emission development strategies (LT-LEDSSs).”).

227 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\textsubscript{P1,5°C} = 75 and GTP\textsubscript{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.

228 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\textsubscript{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\textsubscript{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.”).

229 Cohen-Shields N., Sun T., Hambourg 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\textsubscript{2}e 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)\textsuperscript{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\textsubscript{2}e 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\textsubscript{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.”).


231 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\textsubscript{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\textsubscript{2}…”). See also Mar K. A., Unger C., Waldordorff L. & Butler T. (2022) Beyond CO\textsubscript{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\textsubscript{4}’s impact on climate is distinct from CO\textsubscript{2}’s in several important ways, as described in Section 3. In effect, only the long-term climate impact of CH\textsubscript{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 CH₄’s outsized contribution to near-term climate warming is overlooked…. The focus on CO₂ equivalence under the UNFCCC also leads to an information and transparency gap. The common practice of expressing mitigation targets in terms of aggregate CO₂e—explicitly dismisses other fairness perspectives that would increase their companies’ responsibility for reducing methane emissions (Cady 2020)."

232 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. The timescale of this response is about 4 years here. 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.”

233 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.

234 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.

235 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°C and 2°C targets.”).

236 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.”). 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 CH₄ observations and the way forward, PHIL. TRANS. R. SOC. A 379(2210): 1–14, 11 (“Explaining the renewed and accelerating increase in atmospheric CH₄ 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 CH₄ 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.”; 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., & Claaij 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 CH₄ emissions–climate models. We also show that the decrease in atmospheric CH₄ sinks, which resulted from a reduction of tropospheric OH owing to less NO, 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 CH₄ 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.”); 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 NOx 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.”); Rehder Z., Kleinen T., Kutzbach L., Stepanenko V., Langer M., & Brovkin V. (13 January 2023) *Simulated methane emissions from Arctic ponds are highly sensitive to warming*. *Biogeosci. Discuss. (preprint)*: 1–30, 2, 21 (“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.”); “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 CH₄ m⁻² year⁻¹ °C⁻¹.”); and 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 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 CH₄ is 50% higher than published previously, for SSP3–7.0 it is 131% higher and for SSP5–8.5 it is 130% higher.”).
Unlike CO₂, CH₄ is chemically active, with atmospheric oxidation accounting for approximately 95% of its loss. Among other things, reactions of CH₄ lead to the production of tropospheric O₃ and stratospheric water vapor, and the end product of CH₄ oxidation is CO₂ itself (Forster et al., 2021). In this way, CH₄ 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 CH₄ and its associated photochemical products is provided in Table 1. The chemical reactions of CH₄ 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 CH₄ provides an increased sink for OH [hydroxy radical], reducing the formation of sulfate aerosol (via SO₂ +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 CH₄ (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 CH₄-induced radiative forcing due to stratospheric water vapor.”

238 White House (18 September 2021) Joint US-EU Press Release on the Global Methane Pledge, Statements and Releases (“Methane is a potent greenhouse gas and, according to the latest report of the Intergovernmental Panel on Climate Change, accounts for about half of the 1.0 degree Celsius net rise in global average temperature since the pre-industrial era. Rapidly reducing methane emissions is complementary to action on carbon dioxide and other greenhouse gases, and is regarded as the single most effective strategy to reduce global warming in the near term and keep the goal of limiting warming to 1.5 degrees Celsius within reach.”).

239 Yahoo Finance (8 November 2021) LIVE: President Obama delivers a speech at COP26 climate summit in Glasgow, Scotland, YOUTUBE (from 23:12–23:19).

240 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., Úrge-Vorsatz D., Xiao C., & Yassa 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 CO₂ emissions and including strong emissions reductions of other GHGs, in particular CH₄, 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 CO₂ emissions and non-CO₂ 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 CH₄ (methane) emissions are reduced by 34% [21–57%] below 2019 levels by 2030 and by 44% [31–63%] in 2040 (high confidence). Global CH₄ 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.”).

241 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.”).
242 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.”).

243 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.”).

244 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 CO₂ emissions across the supply chain to the fullest extent practicable.”).

245 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.”).

246 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.”).

247 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 CO2 emissions, as for the CO2-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.”).

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

249 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.”).

250 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 ºC 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 ºC. (Sections 4.1, 4.2 and 4.3)”).

For example, in pathways that limit warming to 1.5°C (>50%) with no or limited emissions, global methane emissions are reduced compared to modelled 2019 emissions by 27% [11–46%] in 2030 and by 52% [36–70%] in 2040; and global CH₄ 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 CO₂ emissions are reduced compared to modelled 2019 emissions by 48% [36–69%] in 2030 and by 80% [61-109%] in 2040; and global CH₄ emissions are reduced by 34% [21–57%] in 2030 and 44% [31-63%] in 2040. There are similar reductions of non-CO₂ emissions by 2050 in both types of pathways: CH₄ is reduced by 45% [25–70%]; N₂O 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 CH₄ 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 CH₄ 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 CO₂ emissions and non-CO₂ 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 CH₄ (methane) emissions are reduced by 34% [21–57%] below 2019 levels by 2030 and by 44% [31–63%] in 2040 (high confidence). Global CH₄ 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).”).

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 CH₄ yr⁻¹ (range 550–594, corresponding to the minimum and maximum estimates of the model ensemble). Of this total, 359 Tg CH₄ 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 CH₄ yr⁻¹ or 50 %-65 %).”).

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.”).


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.”).
Cleaning 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.”).

Cleaning 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.”).

Cleaning 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%.”).

Cleaning 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* (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.”).

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., Kliment 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 CH₄ 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 (Gerber et al. 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 Borgono F., et al. (2019) Improving the sustainability of dairy slurry with a commercial additive treatment, SUSTAINABILITY 11(18): 1–14, 8 (“Natural gas stoves in >40 million U.S. residences release methane (CH₄), 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 extinction. 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 CH₄ 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 (NOₓ) are released into home air and can trigger respiratory diseases. In 32 homes, we measured NOₓ (NO and NO₂) emissions and found them to be linearly related to the amount of natural gas burned (r² = 0.76; p < 0.01). Emissions averaged 21.7 [20.5, 22.9] ng NOₓ J⁻¹, comprised of 7.8 [7.1, 8.4] ng NO₂ 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 NO₂ (100 ppb) within a few minutes of stove usage, particularly in smaller kitchens.”).

262 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 NOₓ 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 (CH₄)—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 extinction. 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 CH₄ 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 (NOₓ) are released into home air and can trigger respiratory diseases. In 32 homes, we measured NOₓ (NO and NO₂) emissions and found them to be linearly related to the amount of natural gas burned (r² = 0.76; p < 0.01). Emissions averaged 21.7 [20.5, 22.9] ng NOₓ J⁻¹, comprised of 7.8 [7.1, 8.4] ng NO₂ 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 NO₂ (100 ppb) within a few minutes of stove usage, particularly in smaller kitchens.”).

263 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 CO₂eq 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.”).
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-CO2 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 CO2eq yr−1) compared with business-as-usual supply patterns with a persistent nutrient gap (5.48 Gt CO2eq yr−1).”).

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 CH4 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 CO2 [38], two orders of magnitude smaller than our MCR estimate of 0.21 ± 0.04°C per effective Pg CH4 removed (figure 2). Accounting for the time delay for carbon dioxide removal due to the lagged response of the deep ocean, the TCRE for CO2 removal may be even lower [39]. If 1 year of anthropogenic emissions was removed (0.36 Pg CH4 [3] and 41.4 Pg CO2 [40]), the transient temperature impact would be almost four times larger for methane than for CO2 (0.075°C compared to 0.02°C). Using this example, however, maintaining a steady-state response of 0.36 Pg CH4 effectively removed would require the ongoing removal of roughly 0.03Pg CH4 yr−1, since a removal rate of E/τ is required to maintain an effective cumulative removal of E.”).

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 CH4 yr−1 (range 550–594, corresponding to the minimum and maximum estimates of the model ensemble). Of this total, 359 Tg CH4 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 CH4 yr−1 or 50%–65%).”).

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 CO2 [38], two orders of magnitude smaller than our MCR estimate of 0.21 ± 0.04°C per effective Pg CH4 removed (figure 2). Accounting for the time delay for carbon dioxide removal due to the lagged response of the deep ocean, the TCRE for CO2 removal...
may be even lower [39]. If 1 year of anthropogenic emissions was removed (0.36 Pg CH₄ [3] and 41.4 Pg CO₂ [40]), the transient temperature impact would be almost four times larger for methane than for CO₂ (0.075°C compared to 0.02°C). Using this example, however, maintaining a steady-state response of 0.36 Pg CH₄ effectively removed would require the ongoing removal of roughly 0.03 Pg CH₄ 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.”).

O’Grady C. (2 November 2021) To slow global warming, some researchers want to pull methane out of the air. SCIENCE (“At a side event at the summit, researchers with the advocacy group Methane Action argued that so-called negative emissions technologies—alongside every trick in the book to reduce emissions—could restore methane to pre-industrial levels and trim an estimated 0.4°C to 0.6°C of warming.”).

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) (“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.”).

White House (11 October 2021) Joint US-EU Press Release on the Global Methane Pledge. Press Release (“At the Major Economies Forum on Energy and Climate (MEF) on September 17, 2021, President Biden and European Commission President Ursula von der Leyen announced, with support from seven additional countries, the Global Methane Pledge—an initiative to be launched at the World Leaders Summit at the 26th UN Climate Change Conference (COP-26) this November in Glasgow, United Kingdom.”).

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

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.”).


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.”).

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 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.).

276 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.”).

277 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.”).

278 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 reduced1. 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.”).

279 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.”).

280 See Inflation Reduction Act, Pub. L. No. 117-169, §21001, 60114 (2022); and United States Senate (28 July 2022) Summary of the Energy Security and Climate Change Investments in the Inflation Reduction Act of 2022; discussed in Friedman L. & Plumer B. (28 July 2022) Surprise Deal Would Be Most Ambitious Climate Action Undertaken by U.S., The NEW YORK TIMES (“The bill would also crack down on leaks of methane, a powerful greenhouse gas, from oil and gas wells, pipelines and other infrastructure. By 2026, polluters would face a penalty of $1,500 per ton of methane that escaped into the atmosphere in excess of federal limits. The methane fee will raise $6.3 billion from the oil and gas industry over a decade, much of which will be reinvested in measures to help prevent methane leaks.”). For further information on what is in the 2022 Inflation Reduction Act, see Paris F., Parlapiano A., Sanger-Katz M.,
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., & Hemdon 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.

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.”).

United States Department of State (17 November 2022) Global Methane Pledge: From Moment to Momentum. Press Release (“The Green Climate Fund, in partnership with the International Fund for Agricultural Development (IFAD), the Food and Agriculture Organization, Global Dairy Platform and Global Methane Hub, $3.5 million of project preparation funding with the objective of leveraging up to $400 million in financing that will help transition dairy systems to lower emission, climate resilient pathways in Kenya, Rwanda, Tanzania and Uganda.”).

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.”).

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).”.

286 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 (O₃) pollution, which hinders crop growth and reduces yields. Here, we assess the relative yield loss in rice, wheat and maize due to O₃ by combining O₃ 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 O₃-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; Aivery 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.”).

287 Mar K. A., Unger C., Walderdorff L., & Butler T. (2022) Beyond CO₂ 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 O₃. 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 (Aivery et al., 2011). Beyond this, however, O₃ damage to plants may significantly reduce the ability of terrestrial ecosystems to absorb carbon, negating some of the enhanced carbon uptake due to CO₂ fertilization that is expected to partially offset rising atmospheric CO₂ concentrations (Sitch et al., 2007, Ciais et al., 2013, Arneth et al., 2010, Ainsworth et al., 2012).”).

288 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.”).

289 Mar K. A., Unger C., Walderdorff L. & Butler T. (2022) Beyond CO₂ equivalence: The impacts of methane on climate, ecosystems, and health, Env’t &L. Science & Pol’y 134: 127–136, 130 (“Importantly, the role of methane’s contribution to O₃ production is expected to increase in the future, as emissions of other anthropogenic precursors (primarily NOx 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 CH₄ concentrations could be a major driver of increased surface O₃ by 2100 under the high-emission scenario developed for the IPCC 5th Assessment report. Ternock et al. (2018) showed that increased O₃ production from rising CH₄ concentrations could offset the reduction in surface O₃ due to reductions in emissions of shorter-lived O₃ precursors.”).

290 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) (Entered into force in accordance with article 17 which reads as follows: “1. The present Protocol shall enter into force on the ninetieth day following the date on which the sixteenth instrument of ratification, acceptance, approval or accession has been deposited with the Depositary. 2.
For each State and organization that meets the requirements of article 14, paragraph 1, which ratifies, accepts or approves the present Protocol or accedes thereto after the deposit of the sixteenth instrument of ratification, acceptance, approval or accession, the Protocol shall enter into force on the ninetieth day following the date of deposit by such Party of its instrument of ratification, acceptance, approval or accession.”).


292 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) (Entered into force in accordance with article 17 which reads as follows: “1. The present Protocol shall enter into force on the ninetieth day following the date on which the sixteenth instrument of ratification, acceptance, approval or accession has been deposited with the Depository. 2. For each State and organization that meets the requirements of article 14, paragraph 1, which ratifies, accepts or approves the present Protocol or accedes thereto after the deposit of the sixteenth instrument of ratification, acceptance, approval or accession, the Protocol shall enter into force on the ninetieth day following the date of deposit by such Party of its instrument of ratification, acceptance, approval or accession.”).


294 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.).

295 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 PM₂.₅, but the converse is not always true; major sources of PM₂.₅ 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 PM₂.₅ 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.

296 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 PM₂.₅ in 2012. Relative risks of mortality were modeled using functions that link long-term exposure to PM₂.₅ 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 PM₂.₅. The greatest mortality impact is estimated over regions with substantial fossil fuel related PM₂.₅, 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.”).  

297 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$4 billion and US$33 billion, of which US$2–28 billion in Asia.”). 

298 Climate & Clean Air Coalition, Black Carbon (last visited 13 June 2023) (Listing solutions to reach 70% reduction in black carbon by 2030). 

299 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 258bcm for 2017). 

300 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.”). 

301 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. Vented 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.”).

302 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. 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.”).

303 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.”).
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. Natl. 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 GtCO₂-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 CO₂.”). 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.”).

England M. R. & Polvani L. M. (2023) *The Montreal Protocol is delaying the occurrence of the first ice-free Arctic summer*. Proc. Natl. 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 Gt of averted ODS emissions results in approximately 7 km² of avoided Arctic sea ice loss.”)

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, worldAvg 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. 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 CO₂ concentrations due to the damaging effect of UV radiation on terrestrial carbon stores.”). 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.

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...
...tributed to Arctic sea ice loss, notably ozonearming over the 1955 to 2005 period.

This second key result of ourween 1955 and 2005 can be attributed to ODS increases. See also Sigmoid 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.”). The relative contribution of ODSs to the total forced Arctic climate change would be smaller. The role of the Montreal P
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 CO2 (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 km2of 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 emissions. 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 km2 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 modelintegrations 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.”).

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)."

311 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$^{19}$ 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$_2$-e) yr$^{-1}$ in 2020 (around 150% of London’s CO$_2$ emissions in 2018$^{20}$ based on 100 yr global warming potentials.”); 4 (“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.”).

312 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 another 0.5 °C 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 °C 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.”).

In the updated 2022 Kigali Amendment scenario, 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."

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."

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.

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.”).

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, 22. 40–41 (“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.”).
316 Theodoridi C., Hillbrand A., Starr C., Mahapatra A., & Taddionio 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 CO₂-equivalent (GtCO₂e) by 2100. Globally, refrigerant management could avoid the gradual release of up to 91 GtCO₂e this century — nearly three times global energy-related carbon dioxide emissions in 2019.

317 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.”).

318 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 (CO₂) 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 GtCO₂e by 2050, and 210–460 GtCO₂e 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 phasedown 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 PgCO₂ equivalent of GHG emissions between 2018 and 2100, thereby making a significant contribution towards keeping the global temperature rise below 2 °C.”).

319 Amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer, 15 October 2016, C.N.872.2016.TREATIES-XXVII.2.f.


321 See HFCBans.com (last visited 14 June 2023) (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.).

322 168 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.

323 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 N₂O 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 N₂O will undo 25% of the benefit gained by the Montreal Protocol to reducing ODS from the ozone layer.”’).

324 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 (N₂O)).

325 Compare the global mean effective radiative forcing values under AR6 for CO₂ and N₂O: 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.

326 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 N₂O 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.”).

327 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 N₂O 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 N₂O emissions were equal to more than 20% the ODP-weighted emissions from CFCs in that year.”).


329 International Energy Agency (2023) CREDIBLE PATHWAYS TO 1.5 °C - FOUR PILLARS FOR ACTION IN THE 2020s, International Energy Agency, 1–15, 12 (Tackling emissions of nitrous oxide (N₂O) is also important to achieve climate
goals. The agricultural sector is responsible for about four-fifths of anthropogenic \( \text{N}_2\text{O} \) emissions. In the STEPS, agricultural \( \text{N}_2\text{O} \) 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 \( \text{N}_2\text{O} \) emissions today are associated with the industry sector and road transport. In the NZE Scenario, energy-related \( \text{N}_2\text{O} \) emissions fall by around 30% between 2021 - 2030, almost entirely associated with reductions in coal and oil use.”).

330 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 \( \text{N}_2\text{O} \) emissions from that in the baseline scenario (SSP2-4.5) to that in the SSP scenario with the strongest \( \text{N}_2\text{O} \) 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 \( \text{N}_2\text{O} \) reduction represents a decrease in anthropogenic \( \text{N}_2\text{O} \) emissions of 3% compared with the baseline scenario when averaged over 2020 –2070.”).

331 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 \( \text{N}_2\text{O} \) or earlier if there are decreases in \( \text{N}_2\text{O} \). However, the effect of future increases in \( \text{N}_2\text{O} \) varies with altitude and also depends on the temporal evolution of other GHGs.”).

332 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 \( \text{N}_2\text{O} \) or earlier if there are decreases in \( \text{N}_2\text{O} \). However, the effect of future increases in \( \text{N}_2\text{O} \) varies with altitude and also depends on the temporal evolution of other GHGs.”).

333 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 \( \text{CO}_2 \), 44% of \( \text{CH}_4 \) and 82% of \( \text{N}_2\text{O} \) global anthropogenic GHG emissions in 2007-2016 (SRCCL SPM A3).”).

334 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 \( \text{CH}_4 \) and \( \text{N}_2\text{O} \) emissions are estimated to average 157 ± 47.1 Mt\( \text{CH}_4 \) yr\(^{-1}\) and 6.6 ± 4.0 Mt\( \text{N}_2\text{O} \) yr\(^{-1}\) or 4.2 ± 1.3 and 1.8 ± 1.1 Gt\( \text{CO}_2\)-eq yr\(^{-1}\) (using IPCC AR6 GWP100 values for \( \text{CH}_4 \) and \( \text{N}_2\text{O} \) respectively between 2010 and 2019.”).


336 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 \( \text{CO}_2 \) and \( \text{CH}_4 \) concentrations to RCP 2.6 levels, \( \text{N}_2\text{O} \) mitigation would become important to avoid exacerbation of both climate change and ozone layer depletion.”).

337 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.”).

338 **SOP, Save Our Planet** (last visited 13 June 2023).

339 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.”). See also Maris S. C., Capra F., Ardenti F., Chioldini 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\(_2\)O 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.”).


341 Environmental Protection Agency (2012) *GLOBAL ANTHROPOGENIC NON-CO\(_2\)* GREENHOUSE GAS EMISSIONS: 1990–2030, 41 (“Between 1990 and 2005, N\(_2\)O emissions from production of nitric and adipic acid has decreased 37 percent, from 200 MtCO\(_2\)e to 126 MtCO\(_2\)e (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\(_2\)O emissions from this source, whereas the OECD is estimated to account for 68 percent of global emissions in 2005.”).

342 Environmental Protection Agency (2019) *GLOBAL NON-CO\(_2\)* GREENHOUSE GAS EMISSION PROJECTIONS & MITIGATION: 2015–2050, 29 (“Taken together, the top 5 countries in terms of baseline emissions represent 85% of all potential global abatement in the source category in 2030. China alone represents 67% of total abatement potential, in part because of its high production capacity and lower adoption of emission controls relative to other large producers of nitric and adipic acid.”).

343 Hasanbeigi A. & Sibal A. (2023) STOPPING A SUPER-POLLUTANT: N\(_2\)O 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\(_2\)O) emissions.”); “Global facilities are currently abating N\(_2\)O 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\(_2\)O 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\(_2\)O 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\(_2\)O 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
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.

344 United Nations Environment Programme & Climate & Clean Air Coalition (2021) Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions, Figure 5.1.

345 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 CO₂ emissions, as for the CO₂-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 °C (range 0.2 to 1.3 °C) at 2040. This is a large portion of the 1.1 °C (range 0.7 to 1.7 °C) 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.”).

346 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., & Navigatsky 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.).

347 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.”).

348 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., von Schuckmann K., Loeb N. G., Osman M. B., Jin Q., Kharecha P., Tselioudis G., Jeong E., Lacis A., Ruedy R., Russell G., Cao J., & Li J. (23 May 2023) **Global warming in the pipeline**, Izv. Atmos. Ocean. Phys. (preprint): 1–62, 33 (“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. 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. Following the additional 2020 regulations, global ship-tracks were reduced more than 50%.”).

349 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/m³ or a kinematic viscosity at 50°C higher than 180 mm²/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.”).

350 Comer B., Osipova L., Geogheff 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.”).

351 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.”).

352 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.”).

353 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. “).

354 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 than halve their black carbon emissions by 2025, exceeding their collective target.

355 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.”).

356 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 Humphert M. (6 December 2021) IMO adopts new measures to reduce black carbon in Arctic shipping, ARCTIC TODAY.

357 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.”).

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

359 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); and 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. 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, 439.”).

360 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 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).”).

361 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$_2$e) y$^{-1}$ (95% CI 20.3–37.4). This is $\geq$30% higher than prior estimates, which did not include the full range of options and safeguards considered here. About half of this maximum (11.3 PgCO$_2$e y$^{-1}$) represents cost-effective climate mitigation, assuming the social cost of CO$_2$ pollution is $\geq$100 USD MgCO$_2$e$^{-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$e$^{-1}$. Most NCS actions—if effectively implemented—also offer water filtration, flood buffering, soil health, biodiversity habitat, and enhanced climate resilience. Work remains to better constrain uncertainty of NCS mitigation estimates. Nevertheless, existing knowledge reported here provides a robust basis for immediate global action to improve ecosystem stewardship as a major solution to climate change.”). See also Moomaw W. R., Masino S. A., & Faison E. K. (2019) Intact Forests in the United States: Proforestation Mitigates Climate Change and Serves the Greatest Good, Perspective, FRONT. FOR. GLOB. CHANGE 2(27): 1–10, 1 (“Climate change and loss of biodiversity are widely recognized as the foremost environmental challenges of our time. Forests annually sequester large quantities of atmospheric carbon dioxide (CO$_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., Groote 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.”).

362 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. ENV’T’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. Forest regrowth may not offset these emissions for many decades—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.”).

363 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.”).
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 high 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 CO2 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 CO2 emissions increased by 46%. Although tropical forests are more immediately threatened by deforestation46 and degradation47, and the future carbon balance will also depend on secondary forest dynamics48 and forest restoration plans49, 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 predict45, 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 CO2 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 CO2 concentrations this century (SSP2-4.5), the rates of CO2 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 CO2 concentrations peak and decline during the 21st century, land and oceans begin to take up less carbon in response to declining atmospheric CO2 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 emissions32 (SSP2-4.5, SSP3-7.0, SSP5-8.5). Additional ecosystem responses to warming not yet fully included in climate models, such as CO2 and CH4 fluxes from wetlands, permafrost thaw and wildfires, would further increase concentrations of these gases in the atmosphere (high confidence).”).

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 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 CO2 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.”).
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 CO₂, we consider the very unlikely limiting case of negligible direct-CO₂ 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 CO₂-fertilization), which translates to dCO₂/dt<0.5 ppm yr⁻¹. Boreal forest dieback is not expected to change the atmospheric CO₂ 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).

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 10 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.”

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 terrestrial 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).”

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) *Comparative 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 CO₂ 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 CO₂ 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).

370 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).”.

371 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).”.

372 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 (Schepfer, 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).”.

373 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 (Bonal et al., 1992).”.

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)."

375 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 °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.), 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.”).

376 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.”).

377 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 al. 50, 2015; Gomes et al., 2019).”).

378 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 ecophysiological, hydroclimatic and sociohydrological interactions.”); discussed in Stockholm 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.

379 Boulton C. A., Lent 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.”).

380 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 interest36,37. 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 point2,36–38. More recently, the possibility of fire-induced tipping has also been suggested5,6. 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 feedbacks 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.”).

381 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.”).

by protecting ecosystems and from drained or burning peatlands are estimated to be up to five percent of all emissions. However, this is not as simple as it
land, Niger Delta’s mangroves, results suggest that the land system
next to the protection of intact peatlands. Therefore, peatland protection and restoration are key for climate change
day degraded peatlands, mainly in the tropical and boreal climate zone, would be rewetted in the coming decades.
would turn into a global net carbon sink by 2100, as projected by current mitigation pathways, if about 60% of present
important strategies to increase negative emissions, but 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.”).

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.”).

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 CO₂ 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.”).

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

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’.”).
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.”).

387 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 CO₂ 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 CO₂ than coal, the first impact of bioenergy use is an increase in atmospheric CO₂. 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 CO₂ 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.

388 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.”).

389 UN Climate Change Conference (2 November 2021) *The Global Forest Finance Pledge: Financing the protection, restoration, and sustainable management of forests* (“Here in Glasgow at COP26, we announce our intention to collectively provide US$12 billion for forest-related climate finance between 2021-2025. This will incentivise results and support action in Official Development Assistance (ODA) eligible forest countries where increased ambition and concrete steps are shown towards ending deforestation by no later than 2030.”); and UN Climate Change Conference (3 November 2021) *COP26 World Leaders Summit – Presidency Summary* (“Over 120 countries covering more than 90% of the world’s forests endorsed the Glasgow Leaders’ Declaration on Forests & Land Use committing to work collectively to halt and reverse forest loss and land degradation by 2030, backed by the biggest ever commitment of public funds for forest conservation and a global roadmap to make 75% of forest commodity supply chains sustainable.”). See also Einhorn C. & Buckley C. (1 November 2021, updated 10 November 2021) *Global Leaders Pledge to End Deforestation by 2030*, The NEW YORK TIMES; and Rannard G. & Gillett F. (2 November 2021) *COP26: World leaders promise to end deforestation by 2030*, BBC NEWS.

390 The White House (2021) *PLAN TO CONSERVE GLOBAL FORESTS: CRITICAL CARBON SINKS*: discussed in United States Department of State (3 November 2021) *Plan to Conserve Global Forests: Critical Carbon Sinks*, Fact Sheet (“At COP26 during the World Leaders Summit Forest Day session on November 2, 2021, the United States announced the Plan to Conserve Global Forests: Critical Carbon Sinks. This decade-long, whole-of-government Plan sets forth the U.S. approach to conserving critical global terrestrial carbon sinks, deploying a range of diplomatic, policy, and financing tools. The first-of-its-kind plan for the U.S. government seeks to catalyze the global effort to conserve and restore the forests and other ecosystems that serve as critical carbon sinks. Subject to Congressional appropriations, by 2030, the United States intends to dedicate up to $9 billion of our international climate funding to support the objectives of the Plan…. The Plan supports collective goals the United States has previously endorsed, including efforts to end natural forest loss by 2030; to significantly increase the rate of global restoration of degraded landscapes and forestlands; and to slow, halt, and reverse forest cover and carbon loss. The Plan outlines the initial approaches the United States intends to deploy to achieve four key objectives: Incentivize forest and ecosystem conservation and forest landscape restoration; Catalyze private sector investment, finance, and action to conserve critical carbon sinks; Build long-term capacity and support the data and monitoring systems that enhance accountability; Increase ambition for climate and conservation action.”).
Jackson R. B., et al. (2021) Atmospheric methane removal: a research agenda, PHILOS. TRANS. R. SOC. A 379(2210): 1–17, 1, 11 (“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 CH₄ 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.”; “Another consideration for active methane-removal systems is the volume of air needed to be processed to remove teragrams of methane. If handling is to be undertaken at large scales, it would make economic sense to convert other greenhouse gases simultaneously, particularly the catalytic reduction of N₂O to N₂. Although our current paper emphasizes methane removal, co-removal of other gases would reduce unit costs.”). 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 CO₂ [38], two orders of magnitude smaller than our MCR estimate of 0.21 ± 0.04°C per effective Pg CH₄ removed (figure 2). Accounting for the time delay for carbon dioxide removal due to the lagged response of the deep ocean, the TCRE for CO₂ removal may be even lower [39]. If 1 year of anthropogenic emissions was removed (0.36 Pg CH₄ [3] and 41.4 Pg CO₂ [40]), the transient temperature impact would be almost four times larger for methane than for CO₂ (0.075°C compared to 0.02°C). Using this example, however, maintaining a steady-state response of 0.36 Pg CH₄ effectively removed would require the ongoing removal of roughly 0.03Pg CH₄ yr⁻¹, since a removal rate of E/τ is required to maintain an effective cumulative removal of E.”). For more history on this proposal, see Jackson R. B., Solomon E. I., Canadell J. G., Cargnello M., & Field C. B. (2019) Methane removal and atmospheric restoration, NAT. SUSTAIN. 2: 436–438, 436 (“In contrast to negative emissions scenarios for CO₂ that typically assume hundreds of billions of tonnes removed over decades and do not restore the atmosphere to preindustrial levels, methane concentrations could be restored to ~750 ppb by removing ~3.2 of the 5.3 Gt of CH₄ currently in the atmosphere. Rather than capturing and storing the methane, the 3.2 Gt of CH₄ could be oxidized to CO₂, a thermodynamically favourable reaction… In total, the reaction would yield 8.2 additional Gt of atmospheric CO₂, equivalent to a few months of current industrial CO₂ emissions, but it would eliminate approximately one sixth of total radiative forcing. As a result, methane removal or conversion would strongly complement current CO₂ and CH₄ emissions-reduction activities. The reduction in short-term warming, attributable to methane’s high radiative forcing and relatively short lifetime, would also provide more time to adapt to warming from long-lived greenhouse gases such as CO₂ and N₂O.”). Klaus Lackner critiqued the Jackson et al. article in a published response, arguing that implementing zeolite mechanisms to facilitate CH₄ removal is not practical. Lackner noted CH₄ removal faces the challenge of extreme dilution in the atmosphere, so “the amount of air that would need to be moved [to facilitate CH₄ removal] would simply be too great” to be economically feasible. However, Lackner did note passive methods of CH₄ removal through the use of zeolites may still be a viable solution. Lackner further argues that N₂O may be a more worthy target for removal due to its long lifetime in the atmosphere; see Lackner K. S. (2020) Practical Constraints on Atmospheric Methane Removal, NAT. SUSTAIN. 3: 357. Jackson et al. published a response to Lackner, acknowledging his stature in the greenhouse gas removal field and his concerns about the feasibility and energy requirements of their proposed mechanism, offering additional explanation about alternative options for use of the captured methane instead of just converting it to CO₂ as suggested in the original study; see Jackson R. B., Solomon E. I., Canadell J. G., Cargnello M., Field C. B., & Abernethy S. (2020) Reply to: Practical constraints on atmospheric methane removal, NAT. SUSTAIN. 3: 358–359. Another study looking at removing non-CO₂ GHGs investigated the potential of using solar chimney power plants (SCPPs) with select photocatalysts (depending on what GHGs desired to be captured). While the SCPP serves as a source of renewable energy that could remove methane and nitrous oxide among other atmospheric pollutants, scaling up the prototype would require a massive amount of land area (roughly 23 times the size of the entire Beijing municipality) and a chimney stretching 1000–1500 m into the air, which limits how practical

392 Nisbet-Jones P. B. R., Fernandez J. M., Fisher R. E., France J. L., Lowry D., Waltham D. A., Woolley Maisch C. A., & Nisbet E. G. (2021) Is the destruction or removal of atmospheric methane a worthwhile option?, PHILOS. TRANS. R. SOC. A 380(2215): 1–12, 5 (“Methane is relatively difficult to oxidize compared to other hydrocarbons. The major destruction options include (i) thermal-catalytic oxidation, which is typically with metal catalysts; (ii) photocatalytic oxidation; (iii) biological uptake by aerobic methanotrophic bacteria or their bio-engineered methane-oxidising enzymes and (iv) removal by uptake on zeolites or porous polymers, with the added benefit of not emitting CO₂ waste.”). See also Ming T., Li W., Yuan Q., Davies P., de Richter R., Peng C., Deng Q., Yuan Y., Caillol S., & Zhou N. (2022) Perspectives on removal of atmospheric methane, ADV. APPL. ENER. 5(100086): 1–9, 1 (“This article reviews proposed methods for atmospheric methane removal at a climatically significant scale. These methods include enhancement of natural hydroxyl and chlorine sinks, photocatalysis in solar updraft towers, zeolite catalyst in direct air capture devices, and methanotrophic bacteria.”).

393 Wanser K., Wong A., Karspeck A., & Esguerra N. (2023) Near-Term Climate Risk and Intervention: A Roadmap for Research, U.S. Research Investment, and International Scientific Cooperation, SilverLining, 40 (“As the essential foundation for any forward path, the global community must aggressively reduce GHG emissions. Today, this should include heighted focus on reducing emissions of substances with the potential for greatest reduction in warming in the near term (e.g., methane, nitrous oxide). Due to the high levels of GHGs already in the atmosphere, society must also aggressively remove GHGs. To do this effectively requires a portfolio that considers the speed, scalability, duration, and ecological impacts of various approaches.”).

394 Advanced Research Projects Agency-Energy (8 April 2021) Reducing Emissions of Methane Every Day of the Year, ARPA-E Programs (“Program Description: REMEDY (Reducing Emissions of Methane Every Day of the Year) is a three-year, $35 million research program to reduce methane emissions from three sources in the oil, gas, and coal value chains: 1) Exhaust from 50,000 natural gas-fired lean-burn engines. These engines are used to drive compressors, generate electricity, and increasingly repower ships. 2) The estimated 300,000 flares required for safe operation of oil and gas facilities. 3) Coal mine ventilation air methane (VAM) exhausted from 250 operating underground mines. These sources are responsible for at least 10% of U.S. anthropogenic methane emissions. Reducing emissions of methane, which has a high greenhouse gas warming potential, will ameliorate climate change.”).

395 Advanced Research Projects Agency-Energy (30 September 2020) Prevention and Abatement of Methane Emissions (“We’re open to all options – but specifically are looking for solutions that: Prevent methane emissions from anthropogenic activities. In other words, solutions which intervene before anthropogenic emissions escape to the atmosphere. Abate methane emissions at their source. Sources include vents, leaks, and exhaust stacks. Remove methane from the air. As mentioned above, methane only lasts about 9 years in the atmosphere. Nature is very good at getting rid of methane using reactions in the atmosphere and methanotrophs in the soil. Maybe we can learn from Nature, and help her out.”). See also Lewnard J. (16 November 2020) REMEDY – Reducing Emissions of Methane Every Day of the Year, ARPA-E Presentation, 7 (“Example Potential Approaches, Not Intended to Limit or Direct… “Geo-engineering”: Accelerate tropospheric reactions; Accelerate soil/methanotroph reactions”).

396 Advanced Research Projects Agency-Energy (2 December 2021) U.S. Department of Energy Awards $35 Million for Technologies to Reduce Methane Emissions, Press Release (“MAHLE Powertrain (Plymouth, MI) will develop a catalytic system to oxidize methane in the exhaust gas of lean-burn natural gas fired engines. (Selection amount: $3,257,089)…. Johnson Matthey, Inc. (Wayne, PA) is developing new technology, which uses a noble metal catalyst to combust the dilute methane in coal mine ventilation systems. (Selection amount: $4,346,015) Massachusetts Institute of Technology (Cambridge, MA) is developing a low-cost copper-based catalyst for reducing methane emissions. (Selection amount: $2,020,903)….”). See also Advanced Research Projects Agency-Energy (2 December 2021) REMEDY—Reducing Emissions of Methane Every Day of the Year: Project Descriptions, Press Release.
Briefing Room; is a technology that captures carbon dioxide directly from the air on 11 September 2019. (11 September 2019) emitted carbon dioxide removal service n internal department’s advanced Energy Science Program to, – reactive rock formations, such as basalts, to form stable minerals providing a permanent and safe carbon sink. The Carbfix imitates and accelerates these natural processes, where carbon dioxide is dissolved in water and the only form of carbon drawdown from the atmosphere. Vast quantities of carbon are naturally stored in rocks. both process, transforms into stone, and remains for over 10,000 years. This makes our carbon term implementation effective and permanent, is what happens after we hand the air captured to the planet by your unavoidable CO₂ emissions. (At Climeworks, we offer carbon dioxide removal for “basically a Jacuzzi, there’s so much natural gas.”).

A Swiss company, Climeworks, deployed the world’s largest direct air capture and storage plant for carbon dioxide, where they work with the Icelandic start-up Carbfix to store carbon by injecting the carbon into subsurface ground, where it reacts with rock formations to turn into rocks within two years. See Climeworks, Carbon dioxide removal: our service to fight global warming (last visited 14 June 2023) (“At Climeworks, we offer carbon dioxide removal for individuals and businesses who want to fight climate change. With our service, you can take action on behalf of the planet by permanently removing your unavoidable CO₂ emissions. To achieve this, we combine our direct air capture technology with permanent underground storage (direct air capture & storage = DAC+S). Direct air capture, as the term implies, is a technology that captures carbon dioxide directly from the air — such as our Orca facility in Hellisheiði, Iceland. Permanent underground storage is what happens after we hand the air-captured CO₂ over to our storage partner — Carbfix. They transport the CO₂ deep underground, where it reacts with basalt rock through a natural process, transforms into stone, and remains for over 10,000 years. This makes our carbon dioxide removal service both effective and permanent.”); and Carbfix, How it works (last visited 14 June 2023) (“Trees and vegetation are not the only form of carbon drawdown from the atmosphere. Vast quantities of carbon are naturally stored in rocks. Carbfix imitates and accelerates these natural processes, where carbon dioxide is dissolved in water and interacts with reactive rock formations, such as basalts, to form stable minerals providing a permanent and safe carbon sink. The
Carbfix process captures and permanently removes CO₂. The technology provides a complete carbon capture and injection solution, where CO₂ dissolved in water – a sparkling water of sorts – is injected into the subsurface where it reacts with favorable rock formations to form solid carbonate minerals via natural processes in about 2 years. For the Carbfix technology to work, one needs to meet three requirements: favorable rocks, water, and a source of carbon dioxide.”); discussed in Rawnsley J. (11 August 2022) Racing against the clock to decarbonise the planet, FINANCIAL TIMES. For a discussion on carbon dioxide storage through a mineral carbonation process, see Snæbjörnsdóttir S. Ó., Sigfússon B., Marieni C., Goldberg D., Gislason S. R., & Oelkers E. H. (2020) Carbon dioxide storage through mineral carbonation, NAT. REV. EARTH ENVIRON. 1: 90–102; Galezka I. M., Stefánsson A., Kleine B. I., Gunnarsson-Robin J., Snæbjörnsdóttir S. Ó., Sigfússon B., Gunnarsdóttir S. H., Weisenberger T. B., & Oelkers E. H. (2022) A pre-injection assessment of CO₂ and H₂S mineralization reactions at the Nesjavellir (Iceland) geothermal storage site, INT. J. GREENH. GAS CONTROL 115(103610): 1–18; and Ratouis T., Snæbjörnsdóttir S. Ó., Voigt M. J., Sigfússon B., Aradóttir E. A., & Hjörleifsdóttir V. (2022) A transport model of long-term CO₂ and H₂S injection into basaltic rocks at Hellisheiði, SW-Iceland, INT. J. GREENH. GAS CONTROL 114(103586): 1–20. In July 2022, Carbfix was awarded 16 billion Icelandic Króna (US $116 million) by the European Union’s Innovation Fund to build the Coda Terminal Plant, which could store up to 3 million tonnes of CO₂ annually by 2031. See also Carbfix (11 July 2022) Carbfix’s Coda Terminal awarded large EU grant (“Carbfix has been selected for grant award from the European Innovation Fund to build the Coda Terminal Plant, a large-scale CO₂ transport and storage hub at Straumsvík, Iceland. The hub will be the first of its kind in the world. Operations are set to commence in mid-2026 and full capacity will be achieved in 2031, when up to 3 million tons of CO₂ will be annually stored by permanently mineralizing it underground.”); and European Commission (12 July 2022) Innovation Fund: EU invests €1.8 billion in clean tech projects” Press Release (“Today, the EU is investing over €1.8 billion in 17 large-scale innovative clean-tech projects with a third round of awards under the Innovation Fund. Grants will be disbursed from the Innovation Fund to help bring breakthrough technologies to the market in energy-intensive industries, hydrogen, renewable energy, carbon capture and storage infrastructure, and manufacturing of key components for energy storage and renewables…. A project in Iceland will build a highly scalable onshore carbon mineral storage terminal with an estimated overall storage capacity of 880 million tonnes of CO₂.”); discussed in (21 July 2022) Carbfix gets the biggest EU grant any Icelandic company has been awarded, ICELAND MONITOR.

International Energy Agency (2022) Direct Air Capture (“Eighteen DAC plants are currently operational in Europe, the United States and Canada. All of these plants are small scale, and the large majority of them capture CO₂ for utilisation – for drinks carbonation, for instance – with only two plants storing the captured CO₂ in geological formations for removal. Only a few commercial agreements are in place to sell or store the captured CO₂, while the remaining plants are operated for testing and demonstration purposes. The first large-scale DAC plant of up to 1 Mt CO₂/year is in advanced development and is expected to be operating in the United States by the mid-2020s. An improved investment environment led to announcements of several new DAC projects in 2021, including the Storegga Dreamcatcher Project (United Kingdom; aimed at carbon removal) and the HIF Haru Oni eFuels Pilot Plant (Chile; producing synthetic fuels from electrolysis-based hydrogen and air-captured CO₂). Synthetic fuels (up to 3 million litres) are also set to be produced by the Norsk e-Fuel AS consortium in Norway by 2024, including (but not using exclusively) CO₂ captured from DAC. In June 2022 1PointFive and Carbon Engineering announced plans to deploy 70 large-scale DAC facilities by 2035 (each with a capture capacity of up to 1 million tonnes per year) under current policy and voluntary and compliance market conditions, while Climeworks announced the construction of their largest plant to date, Mammoth (capture capacity up to 36 000 t CO₂/year), which should become operational by 2024.”), See also Cross J. N., Sweeney C., Jewett E. B., Feely R. A., McElhany P., Carter B., Stein T., Kitch G. D., & Gledhill D. K. (2023) STRATEGY FOR NOAA CARBON DIOXIDE REMOVAL RESEARCH: A WHITE PAPER DOCUMENTING A POTENTIAL NOAA CDR SCIENCE STRATEGY AS AN ELEMENT OF NOAA’S CLIMATE INTERVENTIONS PORTFOLIO, National Oceanic and Atmospheric Administration Special Report.

Wunderling N., Winkelmann R., Rockström J., Loriani S., Armstrong-McKay D., Ritchie P., Sakschewski B., & Dones 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.”).

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 N₂O, slows the rate of warming a decade or two earlier than decarbonization alone and avoids the 2°C threshold altogether. These non-CO₂ 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.”).

Armstrong McKay D. I., Staal A., Abrams J. F., Winkelmann R., Sakschewski B., Lorianni 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., Rockström 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. 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. We argue that cascading effects might be common. Research last year 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. 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., Úrge-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).”).

406 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-CO2 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.”).

407 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.”).

408 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 °C of global warming above pre-industrial levels, with a likely range of 0.8 °C to 1.2 °C. Global warming is likely to reach 1.5 °C between 2030 and 2052 if it continues to increase at the current rate. (high confidence).”). In addition to cutting CO2 emissions and emissions of the super climate pollutants, the IPCC 1.5 °C Report also calculates the need for significant CO2 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 GtCO2 over the 21st century.”).

409 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 CO2) 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.3.

410 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.”).

411 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.”)

412 Hunter D. B., Salzman J. E., & Zaelke D. (2021) Glasgow Climate Summit: COP26, UCLA School of Law, Public Law Research Paper No. 22-02, 3 (“More generally, COP26 may also reflect an evolution (and a vindication) of the Paris Agreement’s more flexible policy approach—an evolution which supported significantly higher climate ambition than was expected and certainly more than would have occurred if COP26 had been hosted in 2020, as originally intended. Four shifts in focus reflect this new architecture; first, the near-unanimous recognition of the impending climate emergency and the need to limit warming to 1.5 degrees Celsius; second, the recognition “that 2030 is the new 2050,” as French President Emmanuel Macron said, and that major emission cuts have to be made in this decade (note also that the U.S.-China Joint Glasgow Declaration marked the first time that the United States and China acknowledged the urgency of climate action in this “critical decade” of the 2020s); third, the recognition that cutting non-CO2 emissions (particularly methane) is essential for slowing warming in the next couple of decades and that cuts to CO2 alone cannot address the near-term emergency; and fourth, the addition of sector-specific approaches in recognition that it is often more efficient and effective to address individual sectors of the economy in reaching climate solutions.”). See also Zaelke D. & Dreyfus G. (29 December 2021) The good, the bad and the ugly of climate change in 2021 — but it’s not too late to act, The Hill; Zaelke D., Picolotti R., & Dreyfus G. (14 November 2021) Glasgow climate summit: A glass half full, The Hill; Bledsoe P., Zaelke D., & Dreyfus G. (8 November 2021) How to Limit Temperature Increases in the Very Near Term, The New York Times; and Zaelke D. (21 September 2021) A new UN climate architecture is emerging focused on need for speed, The Hill.