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

Critical Role of Short-lived Super Climate Pollutants in the Climate Emergency

IGSD Background Note

27 October 2020
About the Institute for Governance & Sustainable Development (IGSD)

IGSD’s mission is to promote just and sustainable societies and to protect the environment by advancing the understanding, development, and implementation of effective and accountable systems of governance for sustainable development.

As part of its work, IGSD is pursuing “fast-action” climate mitigation strategies that will result in significant reductions of climate emissions to limit temperature increase and other climate impacts in the near-term. The focus is on strategies to reduce non-CO₂ climate pollutants, protect sinks, and enhance urban albedo with smart surfaces, as a complement to cuts in CO₂. It is essential to reduce both non-CO₂ pollutants and CO₂, as neither alone is sufficient to provide a safe climate.

IGSD’s fast-action strategies include reducing emissions of the short-lived non-CO₂ climate pollutants—black carbon, methane, tropospheric ozone, and hydrofluorocarbons (HFCs). Reducing HFCs starting with the Kigali Amendment to the Montreal Protocol has the potential to avoid up to 0.5°C of warming by end of century. Parallel efforts to enhance energy efficiency of air conditioners and other cooling appliances during the phase down of HFCs can double the climate benefits at 2050, and by 2060 avoid the equivalent of up to 460 billion tonnes of CO₂.

Institute for Governance & Sustainable Development

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1. Introduction and summary

This IGSD background note summarizes the science supporting the need for fast near-term climate mitigation, including cuts to short-lived climate pollutants and protection of sinks, to slow feedbacks and tipping points. A 10-year fast mitigation sprint is critical for achieving the 2050 net zero target and otherwise addressing the climate emergency.

- Along the way to achieving the 2050 Net Zero target—or better, a Real Zero target—it is critical to select a pathway that not only reduces CO₂ but that also reduces the short-lived climate pollutants (SLCPs)—black carbon, methane, tropospheric ozone, and HFC refrigerants—as fast as possible, along with other fast mitigation strategies, including protection of sinks; this is essential for achieving near-term and long-term climate targets, including the 2050 Net Zero target. (SLCPs are often referred to as “super pollutants” because of their potency.)

- Speed must become a key goal for selecting climate solutions, in order to provide the most avoided warming in the shortest period of time over the next decade or two, to slow the self-reinforcing feedbacks and avoid tipping points, and to protect the most vulnerable people and ecosystems.

- The window for effective mitigation to slow feedbacks and avoid tipping points is shrinking to perhaps 10 years or less, including the window to prevent crashing through the 1.5 °C guardrail.

![Figure 1: Projected warming](image)


- The world could hit the 1.5 °C guardrail by 2030, due to rising emissions, declining particulate air pollution that unmasks existing warming, and natural climate variability.
In the five years between 2020–2024, the annual global temperature is expected to be at least 1 °C warmer than the 1850–1900 average (range of 0.91–1.59 °C), with a one-in-four chance that at least one year could be 1.5 °C warmer, even if only temporarily, according to the World Meteorological Organization.

- The three strategies that are essential for keeping the planet safe are: (i) reducing CO₂, (ii) reducing short-lived climate pollutants (SLCPs), and (iii) removing up to 1,000 billion tons of CO₂ from the atmosphere by 2100, according to the IPCC’s Special Report on 1.5 °C.
- Cutting the SLCPs can avoid 2 to 6 times more warming at 2050 than CO₂ cuts, reducing projected warming in the Arctic by two-thirds and the rate of global warming by half.

2. **Feedbacks and tipping points are key to the planetary emergency**

Evidence from feedbacks and tipping points suggests that we are already in a state of planetary emergency, where both the risk and urgency of the situation are acute.

- Self-reinforcing feedbacks, including the loss of Arctic sea ice, are among the most vulnerable links in the chain of climate protection.

*Figure 2: Climate tipping points*

3. Shrinking Arctic shield

The Arctic is warming at three times the global average, and the extent of Arctic sea ice—a white shield reflecting incoming solar radiating safely back to space—is shrinking.\textsuperscript{12}

- The Arctic is showing signs of a transition to a less frozen climate, with minimum Arctic sea ice extent already likely having made the shift.\textsuperscript{13}
  - On September 15, 2020, the Arctic sea ice reached its annual minimum as the second lowest extent in the satellite record; the 14 Septembers with the least sea ice extent have all been in the last 14 years.\textsuperscript{14}
  - Through late October 2020, the Arctic sea ice has not yet begun freezing in the Laptev Sea, an area known as the “birthplace of ice” for the Arctic Ocean.\textsuperscript{15}
- The Arctic could become nearly ice-free in late summer during the September minimum extent within a decade or two, lessening its heat-reflecting shield.\textsuperscript{16}
  - Conditions free of sea ice over multiple summer months likely occurred during the last interglacial period, providing further independent support for predictions of ice-free conditions in late summer by 2035.\textsuperscript{17}

**Figure 3: Monthly sea ice extent anomalies**

![Northern Hemisphere Extent Anomalies Sep 1979 - 2020](image)

Source: National Snow and Ice Data Center (NSIDC), Sea Ice Index, “Monthly Sea Ice Extent Anomaly Graph” (last accessed 6 October 2020) (“This graph shows monthly ice extent anomalies plotted as a time series of percent difference between the extent for the month in question and the mean for that month based on the January 1981 to December 2010 data. The anomaly data points are plotted as plus signs and the trend line is plotted with a dashed grey line.”).

- In the extreme case where all Arctic sea ice is lost for all sunlit months, climate forcing equivalent to one trillion tons of CO\textsubscript{2} would be added to the climate system—on top of the forcing from the 2.4 trillion tons of CO\textsubscript{2} added in the 270 years since the Industrial Revolution—, and this would advance future warming by 25 years.\textsuperscript{18}
- This additional warming would be the equivalent of adding just over 56 ppm of CO$_2$ to the current CO$_2$ concentration, which reached a seasonal peak of 417 ppm in May 2020.\textsuperscript{19}
- The added forcing in the Arctic would be 21 W/m$^2$; averaged globally it equals 0.71 W/m$^2$ of global forcing,\textsuperscript{20} compared to the 1.83 W/m$^2$ added by anthropogenic emissions of CO$_2$ since the Industrial Revolution.\textsuperscript{21}
- 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; if clouds increase to completely overcast skies over the Arctic, the warming would be equivalent to adding 500 billion tons of CO$_2$ to the atmosphere.\textsuperscript{22}

- Further jeopardizing the future of summer sea ice is the loss of the strong, very old (>4 years old) multi-year sea ice of the Arctic, which is down to just over 1% of the total sea ice; young, first-year ice—which is thinner, more fragile, and more susceptible to decline—now comprises most of the ice pack.\textsuperscript{23}
  - Less sea ice in the Arctic Ocean allows ocean waves to grow larger, allowing for an acceleration of ice breakup and retreat.\textsuperscript{24} Warming Arctic conditions also leads to a greater number of cyclones and more intense cyclones,\textsuperscript{25} that can contribute to Arctic sea ice decline.\textsuperscript{26}
  - Declining Arctic sea ice has created an environment where more of the warmer Atlantic Ocean water enters the Arctic Ocean, which can reduce sea ice thickness.\textsuperscript{27}

\textit{Figure 4: Late winter sea ice in the Arctic}

4. Permafrost emissions of CO₂, methane, and N₂O

The accelerated Arctic warming risks triggering another self-reinforcing feedback—permafrost thaw— which would further amplify warming by releasing CO₂ and methane (CH₄) as well as nitrous oxide (N₂O).

- Of the approximately 15 million square kilometers of permafrost, 3.4 million square kilometers of permafrost have already thawed; and with warming of 1.5 °C approaching, another 4.8 million square kilometers could thaw.
  - Abrupt thaw “will probably occur in <20% of the permafrost zone but could affect half of permafrost carbon”, and models that are considering only gradual permafrost thaw are substantially underestimating permafrost emissions.
  - The amount of carbon stored in permafrost is nearly twice what is already in the atmosphere—1,700 Gt carbon in permafrost versus 850 Gt carbon in the atmosphere.

5. Methane from Arctic Shelf

There also is a risk that methane will be emitted from the shallow seabed of the East Siberian Arctic Shelf as the Arctic ocean warms, which would speed up other global warming impacts.
• Measurements in October 2020 by an international expedition on board a Russian research vessel are showing elevated methane release from the Arctic Shelf, according to a story by Jonathan Watts in The Guardian, ‘Sleeping giant: Arctic methane deposits starting to release, scientists find’ (27 October 2020). 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.”

• 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.38

6. Increasing melt rate of Greenland Ice Sheet

Other tipping points and feedbacks exist between 1.5 ºC and 2 ºC,39 as confirmed by two of the most recent IPCC Special Reports from October 201840 and September 2019.41

• Currently, the best estimate of the threshold for irreversible melting of the Greenland Ice Sheet is 1.6 ºC; and while it may take several millennia to see the full extent of the sea-level rise—which would contribute 5–7 meters if all of Greenland melted—the “timescale of melt depends strongly on the magnitude and duration of the temperature overshoot.”42
  o In the past two decades, the melt rate across Greenland increased 250–575%,43 and the ice discharge from the Greenland Ice Sheet substantially increased and will likely persist in the coming years.44
• 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….“45

7. Persistence of ocean warming

Compounding the risk from feedbacks and tipping points, warming will continue well after emissions stop; about 93% of the energy imbalance accumulates in the oceans as increased heat46, and this will return to the atmosphere on a timescale of decades to centuries after emissions stop.47

8. Limited role of CO2 for near-term cooling

Cutting CO2 emissions by shifting from fossil fuels to clean energy is essential to do as fast as possible, but doing so will reduce co-emitted cooling aerosols along with reduced CO2, offsetting climate benefits and even producing initial warming over the first couple of decades.48

• These reflective particles are emitted during combustion of fossil fuels and currently mask warming of about 0.51 ºC; and while the accumulated CO2 in the atmosphere will continue to cause warming for decades to centuries, the cooling aerosols will fall out of the atmosphere within days to months.49
• Fast cuts to CO2 could avoid 0.1 ºC of warming by 2050 and up to 1.6 ºC by 2100,50 not accounting for warming due to unmasking by reductions in cooling aerosols.51
This would require CO\textsubscript{2} 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.\textsuperscript{52}

If CO\textsubscript{2} emissions were to peak in 2020 (this year) 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 cooling aerosol would still lead to a net warming effect in the near term.\textsuperscript{53}

With a slower decrease in fossil fuel use (though still a large deviation from current emissions and projections), near-term warming from the unmasking as cooling aerosols are reduced within the next two decades is limited to 0.02–0.1 °C.\textsuperscript{54}

**Figure 6: Climate temperature response to reductions in emissions of CO\textsubscript{2}, SLCPs, or both**

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<thead>
<tr>
<th>Year</th>
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<tr>
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<tr>
<td>2200</td>
<td>4.5</td>
</tr>
</tbody>
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9. **Critical role of short-lived climate pollutants**

Aggressive mitigation of short-lived climate pollutants (SLCPs) – methane, tropospheric ozone, black carbon, and hydrofluorocarbons (HFCs) – is critical for near-term and long-term climate protection.

- Cutting SLCPs is the only plausible way to limit warming due to unmasking over the next 20 years:
  - “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 [non-fossil] emissions is the only plausible way in which to decrease warming during that period.”\textsuperscript{55}
  - Eliminating methane emissions from fossil fuel and other anthropogenic sources as well as anthropogenic tropospheric ozone can limit the near-term warming from unmasking to 0.36 °C, as decreasing atmospheric concentrations of these short-
lived species will have a cooling effect that will counteract the warming from eliminating all aerosols from anthropogenic sources.\textsuperscript{56}

- In contrast to the limited amount of warming reduced at 2050 by cutting CO\textsubscript{2}, fast cuts to non-CO\textsubscript{2} SLCPs could avoid up to 0.6 °C of warming by 2050, and up to 1.2 °C by 2100.\textsuperscript{57} which would reduce projected warming in the Arctic by two-thirds and the rate of global warming by half.\textsuperscript{58}
  - The IPCC’s Special Report on Global Warming of 1.5 °C concludes that cutting SLCPs is essential for staying below 1.5 °C.\textsuperscript{59}
  - 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).\textsuperscript{60} The 2016 Kigali amendment to phase down HFCs is welcomed.”\textsuperscript{61}

- 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.\textsuperscript{62}
  - The initial phasedown schedule of the Kigali Amendment avoids about 90% of the potential, or up to 0.44 °C; more mitigation is available from a faster phasedown schedule and from collecting and destroying HFCs at end of product life.\textsuperscript{63}
  - The Kigali Amendment also requires Parties to take best efforts to reduce HFC-23, a byproduct of the production of HCFC-22, and this will provide additional mitigation not included in the 0.5 °C calculation.\textsuperscript{64}
  - Improving energy efficiency of cooling equipment during the HFC phasedown can more than double the climate benefits over the next several decades.\textsuperscript{65}

- Black carbon and tropospheric ozone are local air pollutants and typically addressed under national or regional air pollution laws, as well as through the voluntary programs of the Climate and Clean Air Coalition to Reduce Short-Lived Climate Pollutants (CCAC).\textsuperscript{66}
  - Cutting black carbon and tropospheric ozone provides powerful collateral benefits, potentially saving 2.4 million lives every year, and increasing annual crop production gains by more than 50 million tons, with US$4–33 billion.\textsuperscript{67}
  - California has cut black carbon emissions by 90% under its air pollution laws and provides a model for other jurisdictions.\textsuperscript{68}

- The Arctic is nearly five times more sensitive to black carbon emitted in the Arctic region than from those emissions that originate in the mid-latitudes.\textsuperscript{69} Reducing black carbon is especially beneficial for the Arctic because black carbon not only warms the atmosphere but also facilitates additional warming. Once black carbon is deposited on the snow and ice, it reduces the reflectivity (albedo) and absorbs extra solar radiation, which leads to further melting than pristine snow and ice.\textsuperscript{70}
  - Heavy-Fuel Oil (HFO) used in shipping is a significant source of black carbon, and the International Maritime Organization (IMO) has drafted a proposal to ban it in the Arctic beginning in July 2024 for some ships, with waivers and exemptions for others until July 2029.\textsuperscript{71} (HFO has been banned in the Antarctic since 2011.)\textsuperscript{72}
• If the HFO ban had been in effect in the Arctic in 2019, as currently drafted, it would have banned only 16% of HFO used in the Arctic, and reduced only 5% of the black carbon.73
• However, if the Arctic ban were imposed without the waivers or exemptions, black carbon emissions could have been reduced by 30%.74

• Methane is increasingly being addressed under local and national laws, as well as under voluntary programs. At a global level, reducing methane emissions associated with human activity by 50% over the next 30 years could mitigate global temperature change by 0.18 °C by 2050.75
  • California’s target is to reduce methane emissions by 40% by 2030.76
  • The U.S. Climate Alliance aims to reduce methane emissions across all sectors by 40–50% by 2030,77 which includes reducing emissions from the energy sector by 40–45% by 2025,78 from the waste sector by 40–50% by 2030,79 and from the agricultural sector where emissions can be reduced 30% from enteric fermentation and up to 70% from manure management by 2030.80
  • The European Union’s target is to reduce methane emissions by 40% by 2030, with a draft proposal to increase the target to 50–55% by 2030.81
  • The CCAC calculates for the oil and gas sector that “Absolute reduction target of at least 45% reduction in methane emissions by 2025 and 60% to 75% by 2030…. are realistic and achievable targets, especially in a sector where technology and financing are largely available….82
  • The Clean Air Task Force states that available technology can reduce oil and gas methane emissions by 75%; additionally, 50% of all sector methane emissions reduction are possible at no net cost.83
  • Other strategies are being proposed for removing methane and other non-CO2 greenhouse gases from the atmosphere.84

10. Importance of forests and other sinks

Halting the destruction of our forests and other carbon sinks so they do not turn into sources of CO2 also provides critical fast mitigation, while also saving biodiversity.85

• Already, 17% of the Amazon forest has been deforested, and there is an expected tipping point when 20 to 40% is lost, which will then, without further human interference, turn the forest into a dry savanna.86
• With increased deforestation (including from fires), greater disturbances, and higher temperatures, there is a point at which the Amazon rainforest would be difficult to reestablish.87

11. Conclusion

The IPCC’s Special Report on 1.5 °C presents the three essential strategies for keeping the planet relatively safe: reducing CO2, reducing SLCPs, and removing up to 1,000 billion tons of CO2 from the atmosphere by 2100.88
• Cutting SLCPs is the only known strategy that can slow warming and feedbacks in time to avoid catastrophic and perhaps existential impacts\(^8^9\) from Hothouse Earth,\(^9^0\) other than perhaps solar radiation management, which could cause unknown and potentially unmanageable side effects.

References

1 Molina M., Zaelke D., Sarma K. M., Andersen S. O., Ramanathan V., & Kaniaru D. (2009) Reducing abrupt climate change risk using the Montreal Protocol and other regulatory actions to complement cuts in CO\(_2\) emissions, PROC. NAT’L. ACAD. SCI. 106(49):20616–20621, 20616 (“Current emissions of anthropogenic greenhouse gases (GHGs) have already committed the planet to an increase in average surface temperature by the end of the century that may be above the critical threshold for tipping elements of the climate system into abrupt change with potentially irreversible and unmanageable consequences. This would mean that the climate system is close to entering if not already within the zone of “dangerous anthropogenic interference” (DAI). Scientific and policy literature refers to the need for “early,” “urgent,” “rapid,” and “fast-action” mitigation to help avoid DAI and abrupt climate changes. We define “fast-action” to include regulatory measures that can begin within 2–3 years, be substantially implemented in 5–10 years, and produce a climate response within decades. We discuss strategies for short-lived non-CO\(_2\) GHGs and particles, where existing agreements can be used to accomplish mitigation objectives. Policy makers can amend the Montreal Protocol to phase down the production and consumption of hydrofluorocarbons (HFCs) with high global warming potential. Other fast-action strategies can reduce emissions of black carbon particles and precursor gases that lead to ozone formation in the lower atmosphere, and increase biosequestration, including through biochar. These and other fast-action strategies may reduce the risk of abrupt climate change in the next few decades by complementing cuts in CO\(_2\) emissions.”); and Molina, M., Ramanathan, V. & Zaelke, D. (2020) Best path to net zero: Cut short-lived climate pollutants, BULLETIN OF THE ATOMIC SCIENTISTS (“And let us be clear: By “speed,” we mean measures—including regulatory ones—that can begin within two-to-three years, be substantially implemented in five-to-10 years, and produce a climate response within the next decade or two.”).

2 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, NATURE, Comment, 575:592–595, 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\(^1^1\). 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\(^1^2\).\(^1^3\). We argue that cascading effects might be common. Research last year\(^1^4\) 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\(^1^4\). 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 Steffen W.,, Rockström J., Richardson K., Lenton T. M., Folke C., Liverman D., Summerhayes C. P., Barnosky A. D., Cornell S. E., Crucifix M., Dones J. F., Fetzer I., Lade S. J., Scheffer M., Winkelmann R., & Schellnhuber H. J. (2018) Trajectories of the Earth System in the Anthropocene, PROC. NAT’L. ACAD. SCI. 115(33):8252–8259, 8254; and Richter-Menge J., Druckmiller M. L., Jeffries M. (2019) Executive Summary, in ARCTIC REPORT CARD 2019, 3–4.

3 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 (“Box 2. Risk Categorization of Climate Change to Society. … [A] 2 °C warming would double the land area subject to deadly heat and expose 48% of the population. A 4 °C warming by 2100 would subject 47% of the land area and almost 74% of the world population to deadly heat, which could pose existential risks to humans and mammals alike unless massive adaptation measures are implemented, such as providing air conditioning to the entire population or a massive relocation of most of the population to safer climates. … This bottom 3 billion population comprises mostly subsistent farmers, whose livelihood will be severely impacted, if not destroyed, with a one- to five-year megadrought, heat waves, or heavy floods; for those among the bottom 3 billion of the world’s population who are living in coastal areas, a 1- to 2-m rise in sea level (likely with a
warming in excess of 3 °C) poses existential threat if they do not relocate or migrate. It has been estimated that several hundred million people would be subject to famine with warming in excess of 4 °C (54). However, there has essentially been no discussion on warming beyond 5 °C. Climate change-induced species extinction is one major concern with warming of such large magnitudes (>5 °C). The current rate of loss of species is ~1,000-fold the historical rate, due largely to habitat destruction. At this rate, about 25% of species are in danger of extinction in the coming decades (56). Global warming of 6 °C or more (accompanied by increase in ocean acidity due to increased 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.

Lenton T. M., et al. (2019) Climate tipping points—too risky to bet against, NATURE, Comment, 575:592–595, 592 (“Models suggest that the Greenland ice sheet could be doomed at 1.5 °C of warming3, which could happen as soon as 2030. …The world’s remaining emissions budget for a 50:50 chance of staying within 1.5 °C of warming is only about 500 gigatonnes (Gt) of CO₂. Permafrost emissions could take an estimated 20% (100 Gt CO₂) off this budget, and that’s without including methane from deep permafrost or undersea hydrates. If forests are close to tipping points, Amazon dieback could release another 90 Gt CO₂ and boreal forests a further 110 Gt CO₂. With global total CO₂ emissions still at more than 40 Gt per year, the remaining budget could be all but erased already. …We argue that the intervention time left to prevent tipping could already have shrunk towards zero, whereas the reaction time to achieve net zero emissions is 30 years at best. Hence we might already have lost control of whether tipping happens. A saving grace is that the rate at which damage accumulates from tipping — and hence the risk posed — could still be under our control to some extent.”).

Allen M., et al. (2018) Summary for Policymakers, in IPCC (2018) Global Warming of 1.5 °C, 6 (“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.”).

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

World Meteorological Organization (WMO), et al. (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.”).
The Arctic is burning like never before

— in the context of forcing from black carbon (BC) (and other 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 UNEP & WMO (2011) INTEGRATED ASSESSMENT OF BLACK CARBON AND TROPOSPHERIC OZONE, 262 (“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.”).
12 Pistone, K., Eisenman, I., & Ramanathan, V. (2014) Observational determination of albedo decrease caused by vanishing Arctic sea ice, PROC. NAT’L. ACADEM. SCI. 111(9) 3322-3326 (“The Arctic has warmed by nearly 2 °C since the 1970s, a temperature change three times larger than the global mean (1). During this period, the Arctic sea ice cover has retreated significantly, with the summer minimum sea ice extent decreasing by 40% (2).”)

13 Landrum L. & Holland M. M. (2020) Extremes become routine in an emerging new Arctic, NATURE CLIMATE CHANGE, Online Publication, 1–8, 1 (“The Arctic is rapidly warming and experiencing tremendous changes in sea ice, ocean and terrestrial regions. Lack of long-term scientific observations makes it difficult to assess whether Arctic changes statistically represent a ‘new Arctic’ climate. Here we use five Coupled Model Intercomparison Project 5 class Earth system model large ensembles to show how the Arctic is transitioning from a dominantly frozen state and to quantify the nature and timing of an emerging new Arctic climate in sea ice, air temperatures and precipitation phase (rain versus snow). Our results suggest that Arctic climate has already emerged in sea ice. Air temperatures will emerge under the representative concentration pathway 8.5 scenario in the early- to mid-twenty-first century, followed by precipitation-phase changes. Despite differences in mean state and forced response, these models show striking similarities in their anthropogenically forced emergence from internal variability in Arctic sea ice, surface temperatures and precipitation-phase changes.”).

14 National Snow and Ice Data Center (NSIDC), Arctic sea ice decline stalls out at second lowest minimum (21 September 2020) (“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.”).

15 Zach Labe (@ZLabe), Twitter, 22 October 2020, 10:51PM, Graphic showing Laptev Sea Ice extent and record low regrowth for October 2020 (“A historic event is ongoing in the #Arctic. We have to pay attention to these climate change indicators.”), linked in THE GUARDIAN, J. Watts, Alarm as Arctic sea ice not yet freezing at latest date on record (22 October 2020) (“For the first time since records began, the main nursery of Arctic sea ice in Siberia has yet to start freezing in late October. The delayed annual freeze in the Laptev Sea has been caused by freakishly protracted warmth in northern Russia and the intrusion of Atlantic waters, say climate scientists who warn of possible knock-on effects across the polar region. Ocean temperatures in the area recently climbed to more than 5°C above average, following a record breaking heatwave and the unusually early decline of last winter’s sea ice. The trapped heat takes a long time to dissipate into the atmosphere, even at this time of the year when the sun creeps above the horizon for little more than an hour or two each day. Graphs of sea-ice extent in the Laptev Sea, which usually show a healthy seasonal pulse, appear to have flat-lined. As a result, there is a record amount of open sea in the Arctic. …The Laptev Sea is known as the birthplace of ice, which forms along the coast there in early winter, then drifts westward carrying nutrients across the Arctic, before breaking up in the spring in the Fram Strait between Greenland and Svalbard. If ice forms late in the Laptev, it will be thinner and thus more likely to melt before it reaches the Fram Strait. This could mean fewer nutrients for Arctic plankton, which will then have a reduced capacity to draw down carbon dioxide from the atmosphere.”).

16 Overland J. E. & Wang M. (2013) When will the summer Arctic be nearly sea ice free?, GEOPHYSICAL RESEARCH LETTERS 40:2097–2101, 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.”); see also Guarino M.-V., Sime L. C., Schröeder D., Malmierca-Vallet I., Rosenblum E., Ringer M., Ridley J., Feltham D., Bitz C., Steig E. J., Wolff E., Stroeve J., & Sellar A. (2020) Sea-ice-free Arctic during the Last Interglacial supports fast future loss, NATURE CLIMATE 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 Overland J. E., Wang M., Walsh J. E., & Stroeve J. C. (2014) Future Arctic climate changes: Adaptation and mitigation time scales, EARTH’S FUTURE 2:68–74, 68 (“The climate in the Arctic is changing faster than in midlatitudes. This is shown by increased temperatures, loss of summer sea ice, earlier snow melt, impacts on ecosystems, and increased economic access. Arctic sea ice volume has decreased by 75% since the 1980s.”).

17 Guarino M.-V., et al. (2020) Sea-ice-free Arctic during the Last Interglacial supports fast future loss, NATURE CLIMATE CHANGE 10:928–932, 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.”).

18 Pistone K., Eisenman, I., & Ramanathan, V. (2019) Radiative Heating of an Ice-Free Arctic Ocean, GEOPHYSICAL RESEARCH LETTERS 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 IGSD’s Plain Language Summary of Pistone K., et al. (2019).

19 Pistone K., et al. (2019) Radiative Heating of an Ice-Free Arctic Ocean, GEOPHYSICAL RESEARCH LETTERS 46(13):7474–7480, 7479 (“The estimate of one trillion tons of CO₂ emissions is computed using the following approximate formula: \( f \times \ln[R(x) + R(x)] \) (Myhre et al., 1998). Here \( f \) is the radiative forcing relative to an arbitrary reference value \( R \), \( x \) is the atmospheric CO₂ concentration, and In 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).”)

20 Annual CO₂ concentrations peak in May. See National Oceanic & Atmospheric Administration (NOAA), Rise of CO₂ unabated, NOAA Research News (4 June 2020) (“Atmospheric carbon dioxide measured at Mauna Loa Observatory reached a seasonal peak of 417.1 parts per million for 2020 in May, the highest monthly reading ever recorded, scientists from NOAA and Scripps Institution of Oceanography at the University of California San Diego announced today. This year’s peak value was 2.4 parts per million (ppm) higher than the 2019 peak of 414.7 ppm recorded in May 2019. NOAA scientists reported a May average of 417.1 ppm. Scripps scientists reported an May average of 417.2 ppm. Monthly carbon dioxide (CO₂) values at Mauna Loa first breached the 400 ppm threshold in 2014, and are now at levels not experienced by the atmosphere in several million years.”).

21 Pistone K., et al. (2019) Radiative Heating of an Ice-Free Arctic Ocean, GEOPHYSICAL RESEARCH LETTERS 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 °N) 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)."

22 Etminan M., Myhre G., Highwood E. J., & Shrine K. P. (2016) Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing. GEOPHYSICAL RESEARCH LETTERS 43:12614–12623, 12620 (“The new expressions increase the IPCC AR5 [Myhre et al., 2013a, Table 8.2] RFs for CO₂, CH₄, and N₂O for the period 1750–2011 from 1.82, 0.48, and 0.17 Wm⁻² to 1.83, 0.61, and 0.17 Wm⁻² or by 0.5%, 25%, and 2%, respectively; the difference in the sum of the three forcings is 0.14Wm⁻².”). National Oceanic and Atmospheric Administration (NOAA) calculated that the radiative forcing from CO₂ was 2.044 W/m² in 2018 and 2.076 W/m² in 2019. NOAA Earth System Research Laboratory, The NOAA Annual Greenhouse Gas Index (AGGI) (last updated Spring 2020).

23 Pistone K., et al. (2019) Radiative Heating of an Ice-Free Arctic Ocean, GEOPHYSICAL RESEARCH LETTERS 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.”).

24 Perovich D., Meier W., Tschudi M., Farrell S., Hendricks S., Gerland S., Kaleschke L., Ricker R., Tian-Kunze X., Webster M., & Wood K. (2019) Sea Ice, in ARCTIC REPORT CARD 2019, 29–30 (“The oldest ice (>4 years old), which once dominated within the Arctic Ocean, now makes up just a small fraction of the Arctic Ocean sea 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.”); and World Meteorological Organization (WMO), et al. (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%. “). See also National Snow & Ice Data Center (NSIDC), Tapping the brakes (2 September 2020) (“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.”). Analysis by Zack Labe showed that sea ice for the high Arctic (above 80 °N) was the lowest extent on record. Twitter, Zack Labe, @ZLabe (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.”).

25 Thomson J. & Rogers W. E. (2014) Swell and sea in the emerging Arctic Ocean, GEOPHYSICAL RESEARCH LETTERS 41:3136–3140, 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.”).

26 Day J. J. & Hodges K. I. (2018) Growing Land-Sea Temperature Contrast and the Intensification of Arctic Cyclones, GEOPHYSICAL RESEARCH LETTERS 45:3673–3681, 3680 (“In this study we have investigated near-surface air temperature gradients along the Arctic coastline in a number of reanalysis products and observations and constructed an index for coastal baroclinicity (the AFZ index). We have used this to construct an analog for future climate change using the highest and lowest quartile years of this index as an analog for climate change and performed composite analysis of atmospheric fields, to infer the response of Arctic cyclones to climate change. In summary, we observed: 1. That 2m land temperatures near the Arctic coastline are warming at approximately twice the rate of sea surface temperatures in adjacent regions; 2. that significantly increased Arctic cyclone frequency and intensity, particularly in the Eastern part of the Arctic Ocean, are characteristic of years with high Arctic coastal temperature gradients, compared to low years; and 3. that the sign of this response is consistent with climate model projections, but the magnitude of change in cyclone numbers is higher, suggesting that CMIP models underestimate the sensitivity of the summer storm track to increasing land-sea contrast in the Arctic. Further, because climate change is increasing land-sea contrasts in the Arctic, it seems highly likely that the circulation patterns typical of years with strong AFZ will become more common as the climate warms. Indeed, strengthening of the mean temperature gradients in the AFZ is a robust feature of future climate projections as is an increase in the strength of the Arctic Front Jet (Mann et al., 2017; Nishii et al., 2014). This study shows that this linkage between surface temperature gradients and atmospheric circulation is important for Arctic cyclones, adding weight to previous studies.”).

27 Zhang J., Lindsay R., Schweiger A., & Steele M. (2013) The impact of an intense summer cyclone on 2012 Arctic sea ice retreat, GEOPHYSICAL RESEARCH LETTERS 40:720–726, 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 × 10^9 km^3 d^{-1} before the cyclone, but almost doubled during the cyclone, averaging 0.21 × 10^9 km^3 d^{-1} (or 0.17 × 10^9 km^3 d^{-1} in the ICAPS) during 6–8 August (Figure 2c and Table 1). The enhanced melt is widespread in the ICAPS, but is strongest in the Canada Basin, where ice melt is as high as 0.12 m d^{-1} (Figures 3b and 3c). This explains the large decrease in ice thickness during the storm in these areas (Figures 1j–1l), up to 0.5 m by 10 August (Figure 1l). The simulated ice in most of these areas was already thin on 4 August before the storm (Figures 1i and 2b). It is no surprise that, because of the elevated ice melt, satellite observations showed a much-reduced ice extent there by 10 August (e.g., Figures 1h and 4a).”)

28 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, GEOPHYSICAL RESEARCH LETTERS 47(e2019GL086682):1–10, 1 (“Substantial changes have occurred in the Arctic Ocean in the last decades. Not only sea ice has retreated significantly, but also the ocean at middepth showed a warming tendency. By using simulations we identified a mechanism that intensifies the upward trend in ocean heat supply to the Arctic Ocean through Fram Strait. The reduction in sea ice export through Fram Strait induced by Arctic sea ice decline increases the salinity in the Greenland Sea, which lowers the sea surface height and strengthens the cyclonic gyre circulation in the Nordic Seas. The Atlantic Water volume transport to the Nordic Seas and Arctic Ocean is consequently strengthened. This enhances the warming trend of the Arctic Atlantic Water layer, potentially contributing to the Arctic “Atlantification.” In these processes, the Nordic Seas play the role of a switchyard, while the reduction of sea ice export flux caused by increased air-sea heat flux over the Arctic Ocean is the switchgear. Increasing ocean heat can reduce sea ice thickness, and currently this occurs mainly in certain regions including the western Eurasian Basin near the Fram Strait and the northern Kara Sea (Carmack et al., 2015; Dmitrenko et al., 2014; Ivanov et al., 2012; Onarheim et al., 2014; Polyakov et al., 2010).”). See also Ciavarella A., Cotterill D., Stott P., Kew S., Philip S., van Oldenborgh G. J., Skålevåg A., Lorenz P., Robin Y., Otto F., Hauser M., Seneviratne S. I., Lehner F., & Zolina O. (2020) Prolonged Siberian heat of 2020, World Weather Attribution, 21–22 (“A large, rapid multi-method attribution study, supported by observational and large ensemble model analyses, indicates with high confidence that extremely warm periods such as the 6 months of January–June 2020 over the Siberian region would have been at least 2 °C cooler in a world without human influence. Similar events have a best estimate return time in the current climate of around 130 years and are now more than 600 times as likely to occur as they would have been at the beginning of the 20th century; with the best estimate orders of magnitude larger. By 2050 we expect such a regional warm period in the first 6 months of the year to be at least another 0.5 °C warmer, and possibly up to 5 °C warmer, with similar 6-month regional temperatures becoming correspondingly more frequent. Statements regarding
the very high June daily maximum temperatures (38 °C) such as were reported at Verkhoyansk can be made only with much lower confidence. Nevertheless, results also indicate a large increase in the likelihood of such temperatures and, with more confidence, an increase in extreme daily maxima of more than 1 °C when comparing the climate of 1900 to the present day.”).

29 Lawrence D. M., Slater A. G., Tomas R. A., Holland M. M., & Deser C. (2008) Accelerated Arctic land warming and permafrost degradation during rapid sea ice loss, Geophysical Research Letters 35(L11506):1–6, 5 (“We find that rapid sea ice loss forces a strong acceleration of Arctic land warming in CCSM3 (3.5-fold increase, peaking in autumn) which can trigger rapid degradation of currently warm permafrost and may increase the vulnerability of colder permafrost for subsequent degradation under continued warming. Our results also suggest that talik formation may be a harbinger of rapid subsequent terrestrial change. This sea ice loss – land warming relationship may be immediately relevant given the record low sea ice extent in 2007.”); and Vaks A., Mason A. J., Breitenbach S. F. M., Kononov A. M., Osinzev A. V., Rosenshaft M., Borshevsky A., Gutareva O. S., & Henderson G. M. (2020) Palaeoclimate evidence of vulnerable permafrost during times of low sea ice, Nature 577:221–225, 221 (“The robustness of permafrost when sea ice is present, as well as the increased permafrost vulnerability when sea ice is absent, can be explained by changes in both heat and moisture transport. Reduced sea ice may contribute to warming of Arctic air, which can lead to warming far inland. Open Arctic waters also increase the source of moisture and cause autumn snowfall over Siberia, insulating the ground from low winter temperatures. These processes explain the relationship between an ice-free Arctic and permafrost thawing before 0.4 Ma. If these processes continue during modern climate change, future loss of summer Arctic sea ice will accelerate the thawing of Siberian permafrost.”). See also Nature News, A. Witze, The Arctic is burning like never before — and that’s bad news for climate change (10 September 2020) (“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 megatones 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.”).

30 Schaefer K., Lantuit H., Romanovsky V. E., Schuur E. A. G., & Witt R. (2014) The Impact of the Permafrost Carbon Feedback on Global Climate, Environmental Research Letters 9:1–9, 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 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 Series B Chemical & Physical Meteorology 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).”).

31 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. 19:4257–4268, 4257 (“The microbial by-product nitrous oxide (N₂O), 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 N₂O fluxes, have used chambers to examine small areas (< 50 m²). In late August 2013, we used the airborne eddy-covariance technique to make in situ N₂O flux measurements over the North Slope of Alaska from a low-flying aircraft spanning a much larger area: around 310 km². We observed large variability of N₂O fluxes with many areas exhibiting negligible emissions. Still, the daily mean averaged over our flight campaign was 3.8 (2.2–4.7) mg N₂O 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.”).
Under a 1.5 ºC stabilization scenario, 4.8 (+2.0, 2.2) million km² of permafrost would be lost compared with the 1960–1990 baseline (corresponding to the IPA map, Fig. 1b), and under a 2 ºC stabilization we would lose 6.6 (+2.0, -2.2) million km², over 40% of the present-day permafrost area. Therefore, stabilizing at 1.5 ºC rather than 2 ºC could potentially prevent approximately 2 million km² of permafrost from thawing.

Chadburn S. E., et al. (2017) An observation-based constraint on permafrost loss as a function of global warming, Nature Climate Change 7:340–344 (“Under a 1.5 ºC stabilization scenario, 4.8 (+2.0, -2.2) million km² of permafrost would be lost compared with the 1960–1990 baseline (corresponding to the IPA map, Fig. 1b), and under a 2 ºC stabilization we would lose 6.6 (+2.0, -2.2) million km², over 40% of the present-day permafrost area. Therefore, stabilizing at 1.5 ºC rather than 2 ºC could potentially prevent approximately 2 million km² of permafrost from thawing.”).

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. Nature Geoscience 13:138–143, 138 (“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.”).


Whitman G., Hope C., & Wadhams P. (2013) Vast costs of Arctic change, Nature 499(7459):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 ºC 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 ….”)

38 Dyonisius M. N., Petrenko V. V., Smith A. M., Hua Q., Yang B., Schmitt J., Beck J., Seth B., Bock M., Hmiel B., Vimont I., Menking J. A., Shackleton S. A., Baggenstos D., Bauska T. K., Rhodes R. H., Sperlich P., Beaudette R., Harth C., Kalk M., Brook E. J., Fischer H., Severinghaus J. P., & Weiss R. F. (2020) *Old carbon reservoirs were not important in the deglacial methane budget*, 367 *Science* 907–910, 908 (“Resulting CH$_4$ emissions from old permafrost carbon range from 0 to 53 Tg CH$_4$ per year (table S10) (20) throughout the last deglaciation and may have contributed up to 27% of the total CH$_4$ emissions to the atmosphere (95% CI upper limit) at the end of the OD-B transition (14.42 ka BP). However, we consider this calculation speculative (see section 4.3 of the materials and methods) (20)…. The last deglaciation serves only as a partial analog to current anthropogenic warming, with the most important differences being the much colder baseline temperature, lower sea level, and the presence of large ice sheets covering a large part of what are currently permafrost regions in the NH…. Because the relatively large global warming of the last deglaciation (which included periods of large and rapid regional warming in the high latitudes) did not trigger CH$_4$ emissions from old carbon reservoirs, such CH$_4$ emissions in response to anthropogenic warming also appear to be unlikely.”).

39 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, 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 Lenton T. M., et al. (2019) *Climate tipping points—too risky to bet against*, NATURE, Comment, 575:592–595, 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…”).

40 Hoegh-Guldberg O., Jacob D., & Taylor M. (2018) *CHAPTER 3: IMPACTS OF 1.5 °C OF GLOBAL WARMING ON NATURAL AND HUMAN SYSTEMS*, in *IPCC (2018) GLOBAL WARMING OF 1.5 °C*, 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.”).

41 Abram N., Gattuso J.-P., & Prakash A. (2019) *FRAMING AND CONTEXT OF THE REPORT*, in *IPCC SPECIAL REPORT ON THE OCEAN AND CRYOSPHERE IN A CHANGING CLIMATE*, 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
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.

42 Robinson A., Calov R., & Ganopolski A. (2012) Multistability and critical thresholds of the Greenland ice sheet. NATURE CLIMATE CHANGE 2:429–432, 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 SCIENCE 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., Rogelj J., Childers K., Schewe J., Friel K., Mengel 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 SYSTEM DYNAMICS 7:327–351, 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 4:346–372, 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. 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).

43 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 melting forcing, and suggest that summer warming (see Fig. 2) is an important component of the observed regional melt intensification.

44 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, COMMUNICATIONS EARTH & ENV’T. 1(1):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. Slater T., Hogg A. E., & Mottram R. (2020) Ice-sheet losses track high-end sea-level rise projections, NATURE CLIMATE CHANGE, Comment, Online Publication, 1–3, 1 (“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 snowfall — 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. BBC NEWS, J. Amos, Climate change: Warmth shatters section of Greenland ice shelf (14 September 2020) (“A big chunk of ice has broken away from the Arctic's largest remaining ice shelf - 79N, or Nioghalvfjerdsfjorden - in north-east 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.”).

45 Lenton T. M., et al. (2019) Climate tipping points—too risky to bet against, NATURE, Comment, 575:592–595, 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…”).

46 Cheng L., Abraham J., Hausfather Z., & Trenberth K. E. (2019) How fast are the oceans warming?, SCIENCE 363(6423):128–129, 128 (“About 93% of the energy imbalance accumulates in the ocean as increased ocean heat content (OHC).”).

In the case of a gas with a 10-y lifetime, for example, energy is slowly stored in the ocean during the period when concentrations are elevated, and this energy is returned to the atmosphere from the ocean after emissions cease and radiative forcing decays, keeping atmospheric temperatures somewhat elevated for several decades. Elevated temperatures last longer for a gas with a 100-y lifetime because, in this case, radiative forcing and accompanying further ocean heat uptake continue long after emissions cease. As radiative forcing decays further, the energy is ultimately restored from the ocean to the atmosphere. Fig. 3 shows that the slow timescale of ocean heat uptake has two important effects. It limits the transfer of energy to the ocean if emissions and radiative forcing occur only for a few decades or a century. However, it also implies that any energy that is added to the ocean remains available to be transferred back to the atmosphere for centuries after cessation of emissions.”

48 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).

49 Lelieveld J., Klingmüller K., Pozzer A., Burnett R. T., Haines A., & Ramanathan V. (2019) Effects of fossil fuel and total anthropogenic emission removal on public health and climate, Proc. Nat’l. Acad. Sci. 116(15):7192–7197, 7194 (“Finally, our model simulations show that fossil-fuel-related aerosols have masked about 0.51(±0.03) °C of the global warming from increasing greenhouse gases (Fig. 3). The largest temperature impacts are found over North America and Northeast Asia, being up to 2 °C. By removing all anthropogenic emissions, a mean global temperature increase of 0.73±0.03 °C could even warm some regions up to 3 °C. Since the temperature increase from past CO2 emissions is irreversible on human timescales, the aerosol warming will be unleashed during the phaseout (11, 19–22).”


51 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. 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, 10320 (“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 in 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. SSB vs. S7).”); and Xu Y. & Ramanathan V. (2017) Well below 2 °C: Mitigation strategies for avoiding dangerous to catastrophic climate changes, Proc. Nat’l. Acad. Sci. 114(39):10315–10323, Table S1.

52 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 Info, 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).”)

53 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 Info, 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)."

and Xu Y. & Ramanathan V. (2017) Well below 2 °C: Mitigation strategies for avoiding dangerous to catastrophic climate changes, PROC. NAT'L. ACAD. SCI. 114(39):10315–10323, Supplemental Info, 7 (Table S1. The contribution of individual mitigation measures to the warming in the 21st century.).

54 Shindell D. & Smith C. J. (2019) Climate and air-quality benefits of a realistic phase-out of fossil fuels, NATURE 573:408–411, 409 (“These results differ greatly from the idealized picture of a near-instantaneous response to the removal of aerosol cooling followed by a slow transition to dominance by the effects of CO₂. In these more plausible cases, the temperature effects of the reduction in CO₂, SO₂ and CH₄ roughly balance one another until about 2035. After this, the cooling effects of reduced CO₂ continue to increase, whereas the warming induced by a reduction in SO₂ and the cooling induced by the reduction in CH₄ taper off, such that the cooling induced by the reduction in CO₂ dominates (Fig. 3). Examining the effects of CO₂ and SO₂ alone (Fig. 3d), the faster response of SO₂ to the changes in emissions means that the net effect of these two pollutants would indeed be a short-term warming—but a very small one, of between 0.02 °C and 0.10 °C in the ensemble mean temperature response (up to 0.30 °C for the 95th percentile across pathways). Accounting for all fossil-related emissions (Fig. 3e), any brief climate penalty decreases to no more than 0.05 °C (0.19 °C at the 95th percentile), with the smaller value largely due to the additional near-term cooling from reductions in methane. Nearly all the warming in the 2020s and 2030s (Fig. 2) is therefore attributable to the effect of the residual emissions (mainly of CO₂) during the gradual fossil phase-out, as well as the response to historical emissions.”).

55 Shindell D. & Smith C. J. (2019) Climate and air-quality benefits of a realistic phase-out of fossil fuels, NATURE 573:408–411 (“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.”).

56 Lelieveld J., et al. (2019) Effects of fossil fuel and total anthropogenic emission removal on public health and climate, PROC. NAT'L. ACAD. SCI. 116(15):7192–7197, 7194 (“Some near-term mitigation can be achieved from the simultaneous reduction of short-lived greenhouse gases such as methane (CH₄), O₃, and hydrofluorocarbons (HFCs) (15, 23–25). Fossil-fuel-related CH₄ emissions constitute nearly 20% of the total source, and removing all anthropogenic CH₄ (nearly 60% of the source), in addition to anthropogenic O₃, would limit the near-term warming to 0.36±(0.06) °C. While the current climate forcing of HFCs is still small, it will be critical to prevent increases in the future, as they are potent greenhouse gases (26). Table 1 presents the unavoidable net warming from emission control measures that simultaneously affect aerosols and greenhouse gases, which have many sources in common. SI Appendix, Table S1 lists these results for all countries, including the uncertainty intervals.”).

57 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).”).

58 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.”); see also UNEP & WMO (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone, 262 (“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.”).

59 Allen M., et al. (2018) Chapter 1: Framing and Context, in IPCC (2018) Global Warming of 1.5 °C, 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).”.


62 Xu Y., Zaelke D., Velders G. J. M., & Ramanathan V. (2013) The role of HFCs in mitigating 21st century climate change, Atmos. Chem. & Phys. 13:6083–6089, 6083 (“Here we show that avoiding production and use of high-GWP (global warming potential) HFCs by using technologically feasible low-GWP substitutes to meet the increasing global demand can avoid as much as another 0.5 °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 CO2-only mitigation scenarios, significantly reducing the rate of warming and lowering the probability of exceeding the 2 °C warming threshold during this century.”).

63 World Meteorological Organization (WMO), United Nations Environment Programme (UNEP), National Oceanic and Atmospheric Administration (NOAA), National Aeronautics and Space Administration (NASA), & European Commission (2018) Executive Summary: Scientific Assessment of Ozone Depletion: 2018, Global Ozone Research and Monitoring Project-Report No. 58, ES.22 (“The Kigali Amendment is projected to reduce future global average warming in 2100 due to HFCs from a baseline of 0.3–0.5 °C to less than 0.1 °C (Figure ES-4). If the global production of HFCs were to cease in 2020, the surface temperature contribution of the HFC emissions would stay below 0.02 °C for the whole 21st century. The magnitude of the avoided temperature increase, due to the provisions of the Kigali Amendment (0.2 to 0.4 °C) is substantial in the context of the 2015 UNFCCC Paris Agreement, which aims to limit global temperature rise to well below 2.0 °C above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 °C.”); 2.40–2.41 (“With the Kigali Amendment and national and regional regulations, the future production and consumption of HFCs is strongly limited (Table 2-1). Under the provisions of the Amendment, the contribution of HFCs to the global average surface temperature is projected to reach a maximum around 2060, after which it slowly decreases to about 0.06°C by 2100 (Figure 2-20). In contrast, the surface temperature contribution from HFCs in the baseline scenario is 0.3–0.5°C in 2100 (based on Xu et al., 2013 and Velders et al., 2015). The difference in projected temperatures is relevant in the context of the 2015 UNFCCC Paris Agreement, which aims to limit the global temperature increase to well below 2°C relative to pre-industrial levels.”).

64 World Meteorological Organization (WMO), United Nations Environment Programme (UNEP), National Oceanic and Atmospheric Administration (NOAA), National Aeronautics and Space Administration (NASA), & European Commission (2018) Executive Summary: Scientific Assessment of Ozone Depletion: 2018, Global Ozone Research and Monitoring Project-Report No. 58, ES.22 (“The Kigali Amendment is projected to reduce future global average warming in 2100 due to HFCs from a baseline of 0.3–0.5 °C to less than 0.1 °C (Figure ES-4). If the global production of HFCs were to cease in 2020, the surface temperature contribution of the HFC emissions would stay below 0.02 °C for the whole 21st century. The magnitude of the avoided temperature increase, due to the provisions of the Kigali Amendment (0.2 to 0.4 °C) is substantial in the context of the 2015 UNFCCC Paris Agreement, which aims to limit global temperature rise to well below 2.0 °C above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 °C.”); 2.40–2.41 (“With the Kigali Amendment and national and regional regulations, the future production and consumption of HFCs is strongly limited (Table 2-1). Under the provisions of the Amendment, the contribution of HFCs to the global average surface temperature is projected to reach a maximum around 2060, after which it slowly decreases to about 0.06°C by 2100 (Figure 2-20). In contrast, the surface temperature contribution from HFCs in the baseline scenario is 0.3–0.5°C in 2100 (based on Xu et al., 2013 and Velders et al., 2015). The difference in projected temperatures is relevant in the context of the 2015 UNFCCC Paris Agreement, which aims to limit the global temperature increase to well below 2°C relative to pre-industrial levels.”).
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The Climate & Clean Air Coalition to Reduce Short-Lived Climate Pollutants (The CCAC identifies solutions to the 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.).

Integrated Assessment of Black Carbon and Tropospheric Ozone, 193 (Implementing all measures could avoid 2.4 million premature deaths (within a range of 0.7–4.6 million) associated with reductions in PM2.5, associated with 5.3–37.4 million years of life lost (YLL), based on the 2030 population.”); and United Nations Environment Programme (UNEP) & World Meteorological Organization (WMO) (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone, 201 (“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.”).

California Air Resources Board (CARB), Research Synthesis #17-01 "How California is Giving Soot the Boot!" (April 2017) (“California’s clean air rules reduced black carbon emissions by 90% since the 1960s, providing immediate climate and health benefits. Ongoing efforts will cut the remaining amount in half by 2030.”).

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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 (AMAP) (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 (IEA) (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.”).

71 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, White Paper, International Council on Clean Transport (ICCT), 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, 2017). 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 International Council on Clean Transport (ICCT), The International Maritime Organization’s proposed Arctic heavy fuel oil ban: Likely implications and opportunities for improvement (3 September 2020) (“In February 2020, at the seventh session of the International Maritime Organization (IMO)’s Pollution Prevention and Response Sub-Committee, delegates agreed on draft text of a ban on the use and carriage for use of heavy fuel oil (HFO) in the Arctic. … While the ban would start to apply in July 2024, exemptions and waivers included in the draft text would allow some ships to use HFO until July 2029.”); and Climate Home News, C. Farand, Loopholes in Arctic heavy fuel oil ban defer action to the end of the decade (3 September 2020) (“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.”).

72 Comer B., et al. (2020) The International Maritime Organization’s proposed Arctic heavy fuel oil ban: Likely impacts and opportunities for improvement, White Paper, International Council on Clean Transport (ICCT), 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."

29
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 CLIMATE HOME NEWS, C. Farand, Loopholes in Arctic heavy fuel oil ban defer action to the end of the decade (3 September 2020) (“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.”).

73 Comer B., et al. (2020) The International Maritime Organization’s proposed Arctic heavy fuel oil ban: Likely impacts and opportunities for improvement, White Paper, International Council on Clean Transport (ICCT), 10–11 (“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.”); see also Comer B., et al. (2020) The International Maritime Organization’s proposed Arctic heavy fuel oil ban: Likely impacts and opportunities for improvement, White Paper, International Council on Clean Transport (ICCT), 19 (Figure 18).

74 Comer B., et al. (2020) The International Maritime Organization’s proposed Arctic heavy fuel oil ban: Likely impacts and opportunities for improvement, White Paper, International Council on Clean Transport (ICCT), 19 (Figure 18).

75 European Commission (2020) Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on an EU strategy to reduce methane emissions, 1 (“At a global level, reducing methane emissions associated with human (anthropogenic) activity by 50% over the next 30 years could reduce global temperature change by 0.18 degrees Celsius by 2050. The EU has reduction targets for 2030 for all greenhouse gases, with anthropogenic methane emissions covered by binding national emission reduction targets under the Effort Sharing Regulation (ESR). However, there is currently no policy dedicated to the reduction of anthropogenic methane emissions.”)

76 S.B. 1383, 2015–2016 Leg. (Cal. 2016) (“The California Global Warming Solutions Act of 2006 designates the State Air Resources Board as the state agency charged with monitoring and regulating sources of emissions of greenhouse gases. The state board is required to approve a statewide greenhouse gas emissions limit equivalent to the statewide greenhouse gas emissions level in 1990 to be achieved by 2020. The state board is also required to complete a comprehensive strategy to reduce emissions of short-lived climate pollutants, as defined, in the state. This bill would require the state board, no later than January 1, 2018, to approve and begin implementing that comprehensive strategy to reduce emissions of short-lived climate pollutants to achieve a reduction in methane by 40%, hydrofluorocarbon gases by 40%, and anthropogenic black carbon by 50% below 2013 levels by 2030, as specified. The bill also would establish specified targets for reducing organic waste in landfills.”).

77 United States Climate Alliance, From SLCP Challenge to Action: A roadmap for reducing short-lived climate pollutants to meet the goals of the Paris Agreement (September 2018), 11 (“Significant additional opportunities exist to cut methane emissions quickly and cost effectively across the U.S. Capturing the full potential of expected reduction opportunities, as described in Appendix A, could reduce methane emissions by 40-50 percent below current levels in the U.S. Climate Alliance. Existing and emerging strategies and technologies can achieve these reductions by 2030.”).

78 United States Climate Alliance, From SLCP Challenge to Action: A roadmap for reducing short-lived climate pollutants to meet the goals of the Paris Agreement (September 2018), 11 (“There is an opportunity for the U.S.
Climate Alliance to help fulfill the commitment by the U.S., Canada, and Mexico to implement federal regulations on new and existing sources in the oil and gas sector to reduce methane emissions by 40-45 percent below 2012 levels by 2025.”). In 2016, the U.S., Canada, and Mexico committed to reducing methane emissions in the oil and gas sector by 40–45% by 2025 (compared to 2012 levels). Canada, Mexico, & United States of America (2016) Leaders’ Statement on a North American Climate, Clean Energy, and Environment Partnership, 2 (“Today, Mexico will join Canada and the United States in committing to reduce their methane emissions from the oil and gas sector – the world’s largest methane source – 40% to 45% by 2025, towards achieving the greenhouse gas targets in our nationally determined contributions. To achieve this goal, the three countries commit to develop and implement federal regulations to reduce emissions from existing and new sources in the oil and gas sector as soon as possible. We also commit to develop and implement national methane reduction strategies for key sectors such as oil and gas, agriculture, and waste management, including food waste.”).

79 United States Climate Alliance, From SLCP Challenge to Action: A roadmap for reducing short-lived climate pollutants to meet the goals of the Paris Agreement (September 2018), 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.”).

80 United States Climate Alliance, From SLCP Challenge to Action: A roadmap for reducing short-lived climate pollutants to meet the goals of the Paris Agreement (September 2018), 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.”).

81 Joint Research Centre, European Commission (2018) Global Trends of Methane Emissions and Their Impacts on Ozone Concentrations, 4 (“To fulfil the targets of the Kyoto Protocol, the EU introduced in 2009 the Climate & Energy package (406/2009/EC) with an overall GHG emission reduction objective of 20% by 2020 compared to 1990. The 2030 climate and energy framework strengthened these objectives to reach an overall GHG reduction of 40%, and 30% in the non-ETS sector by 2030 compared to 2005 and outlined nationally determined contributions for GHG reduction under the 2015 Paris Agreement.”); see also EURACTIV.com, S. van Renssen, EU turns to methane emissions in fight against global warming (3 December 2019, updated 4 December 2019) (“New Commission President Ursula von der Leyen wants to raise the EU’s greenhouse gas emissions reduction target for 2030 from 40% to 50-55%, compared to 1990. … Methane emissions are in the spotlight with a new EU gas policy package in the works and intense debate over the role of gas in decarbonising the EU’s energy system.”); European Commissions, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on an EU Strategy to reduce methane emissions, DRAFT (“The EU’s 2030 Impact Assessment for non-CO₂ emissions found methane to be the dominant non-CO₂ greenhouse gas in the EU, and that stepping up the level of ambition for greenhouse gas emission reduction from 50-55% by 2030 will require an accelerated initiative on methane emissions. Current baseline non-CO₂ emissions scenarios already anticipate a decrease of methane emissions in the EU by 45% compared to 1990 by 2030. However, modelling suggests that reductions of 53-55% will be necessary to meet climate targets by that date. Moreover, in the EU’s Long Term Strategy scenarios, projections indicate that methane emissions could rise again from 2030 to 2050. It is therefore important that the EU sets out a methane strategy with an enduring impact beyond medium-term objectives. At a global level, reducing methane emissions associated with human activity by 50% over the next 30 years could mitigate global temperature change by 0.18 degrees Celsius by 2050. The EU has reduction targets for 2030 across all
greenhouse gases, with overall methane emissions covered in the Effort Sharing Regulation. However, there is currently no specific regime in place for the reduction of anthropogenic methane emissions.”).

82 A Global Alliance to Significantly Reduce Methane Emissions in the Oil and Gas Sector by 2030, Climate and Clean Air Coalition to Reduce Short-Lived Climate Pollutants (“Absolute reduction target of at least 45% reduction in methane emissions by 2025 and 60% to 75% by 2030…. are realistic and achievable targets, especially in a sector where technology and financing are largely available, and innovation supports even larger reductions. … Re...
“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 MgCO₂⁻¹ 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.”). 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. FRONT. FOR. GLOB. CHANGE 2 (“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 (CO₂), 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 I.5 Degree Warming Report by the Intergovernmental Panel on Climate Change identifies reforestation and afforestation as important strategies to increase negative emissions, but they face significant challenges: afforestation requires an enormous amount of additional land, and neither strategy can remove sufficient carbon by growing young trees during the critical next decade(s). In contrast, growing existing forests intact to their ecological potential—termed proforestation—is a more effective, immediate, and low-cost approach that could be mobilized across suitable forests of all types. Proforestation serves the greatest public good by maximizing co-benefits such as nature-based biological carbon sequestration and unparalleled ecosystem services such as biodiversity enhancement, water and air quality, flood and erosion control, public health benefits, low impact recreation, and scenic beauty.”); and World Wildlife Fund (2020) LIVING PLANET REPORT 2020—BENDING THE CURVE OF BIODIVERSITY LOSS, Almond R.E.A., Grooten M., and Petersen T. (eds.), 5 (“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.”).

85 Griscom B. W., Adams J., Ellis P. W., Houghton R. A., Lomax G., Miteva D. A., Schlesinger W. H., Shoch D., Siikamäki J. V., Smith P., Woodbury P., Zganjar C., Blackman A., Campari J., Conant R. T., Delgado C., Elias P., Gopalakrishna T., Hamisk M. R., Herrero M., Kiesecker J., Landis E., Laestadius L., Leavitt S. M., Minnemeyer S., Polasky S., Potapov P., Putz F. E., Sanderman J., Silvius M., Wollenberg E., & Fargione J. (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 MgCO₂⁻¹ 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.”). 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. FRONT. FOR. GLOB. CHANGE 2 (“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 (CO₂), 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 I.5 Degree Warming Report by the Intergovernmental Panel on Climate Change identifies reforestation and afforestation as important strategies to increase negative emissions, but they face significant challenges: afforestation requires an enormous amount of additional land, and neither strategy can remove sufficient carbon by growing young trees during the critical next decade(s). In contrast, growing existing forests intact to their ecological potential—termed proforestation—is a more effective, immediate, and low-cost approach that could be mobilized across suitable forests of all types. Proforestation serves the greatest public good by maximizing co-benefits such as nature-based biological carbon sequestration and unparalleled ecosystem services such as biodiversity enhancement, water and air quality, flood and erosion control, public health benefits, low impact recreation, and scenic beauty.”); and World Wildlife Fund (2020) LIVING PLANET REPORT 2020—BENDING THE CURVE OF BIODIVERSITY LOSS, Almond R.E.A., Grooten M., and Petersen T. (eds.), 5 (“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.”).
Allen M., et al. (2018) Summary for Policymakers, in IPCC (2018) Global Warming of 1.5 °C, 6 (“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.”).

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 (“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.”).

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.”).