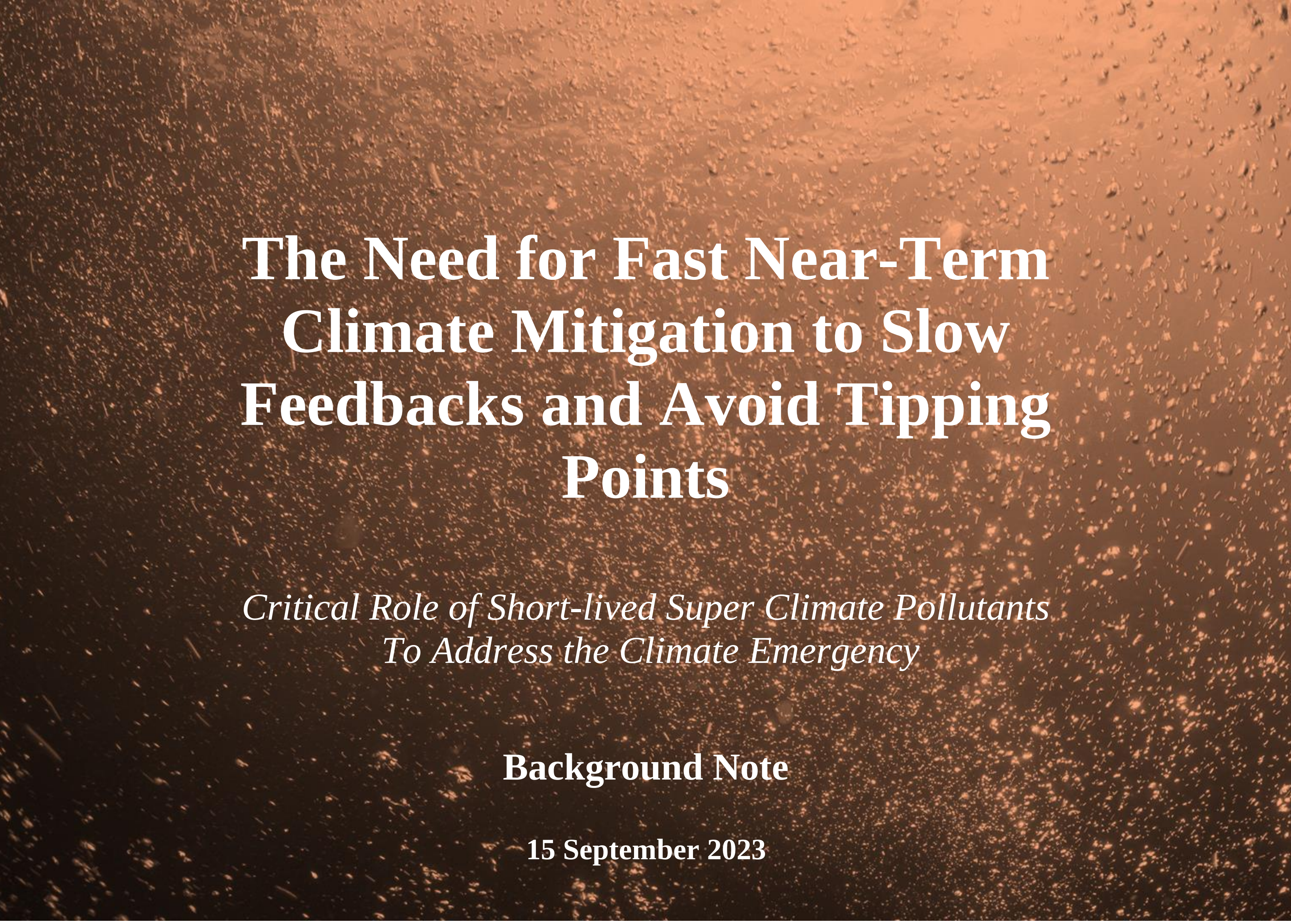

The Need for Fast Near-Term Climate Mitigation to Slow Feedbacks and Avoid Tipping Points

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

Background Note

15 September 2023

Institute for Governance
& Sustainable Development (IGSD)

Center for Human Rights and
Environment (CHRE/CEDHA)

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**Institute for Governance
& Sustainable Development**

**Center for Human Rights and
Environment (CHRE/CEDHA)**

About the Institute for Governance & Sustainable Development (IGSD)

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

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

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

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

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

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

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

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

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

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Table of Contents

List of Figures and Tables

1. Introduction and summary

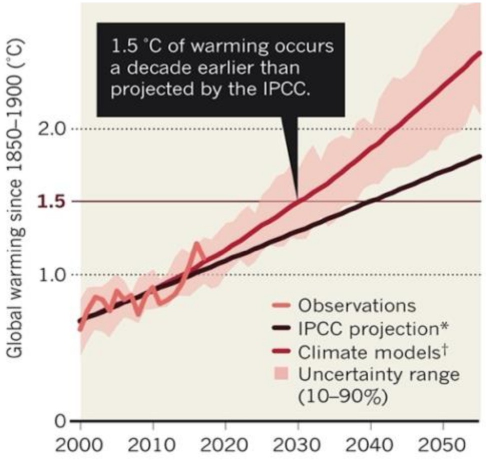
This *Background Note* summarizes the science supporting the need for fast climate mitigation to slow warming in the near term (2023–2041). It focuses on the importance of cutting super climate pollutants and protecting carbon sinks as the most effective ways to slow self-amplifying feedbacks and avoid,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

Climate change presents two challenges, or races, that we must simultaneously run and win: the race to stabilize the climate in the longer term, and the race to slow the rate of warming in the near term to reduce the risk of climate extremes that scale with the rate of warming and threaten to accelerate self-amplifying feedbacks and trigger a cascade of irreversible tipping points. Cutting super climate pollutants, in particular the short-lived climate pollutants (SLCPs)—black carbon, methane (CH_4), tropospheric ozone (O_3), and hydrofluorocarbons (HFCs)—can avoid four times more warming at 2050 than cutting CO_2 only,[1] and reduce projected warming in the Arctic by two-thirds and the rate of global warming by half.[2] Reducing climate risks and staying within the limits to adaptation are critical to building resilience.[3]

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

The window for effective mitigation to slow self-amplifying feedbacks and avoid, or at least delay, irreversible tipping points is shrinking to perhaps 10 years or less, including the window to prevent crashing through the 1.5 °C guardrail. At 2 °C of warming the risks of triggering "relatively large, abrupt and sometimes irreversible changes in systems" become high, according to the Intergovernmental Panel on Climate Change's (IPCC) 6th Assessment Report (AR6).[4] Because extreme climate impacts depend on the *rate of warming* as well as the total warming, the accelerating rate of increases in CO_2 and other warming climate pollutants is particularly troubling.[5] Continuing record climate emissions mean that the rate of warming could increase from 0.2 °C per decade to 0.25–0.32 °C per decade over the next 25 years.[6]

Figure 1. Projected warming



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

Box 1. Types of temperature and warming as defined by the IPCC

The IPCC differentiates among five kinds of temperature/warming:[7]

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

- Observed *annual* temperature in 2022 was 1.2 °C above pre-industrial levels and continues to warm at a rapid rate, which is exacerbated by the start of an El Niño warming pattern in June 2023 and expected to last through late 2024.[8] According to the Copernicus weather service, "we have already entered uncharted territory" in global temperature extremes.[9]
- There is a 66% chance that global annual temperatures will exceed 1.5 °C for at least one year between 2023 and 2027 and a 32% chance that the five-year mean from 2023–2027 will exceed this threshold, according to the World Meteorological Organization.[10] With the end of the triple La Niña, warmer El Niño conditions could push 2023 to the warmest year on record[11] and 2024 to 1.4–1.5 °C.[12]

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

- The *total warming* over 2013–2022 was 1.15 °C higher than the 1850–1900 average.[13]
- "Each of the last four decades has been successively warmer than any decade that preceded it since 1850."[14]

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

- The 10-year average *current human-induced global warming* over 2013–2022 was 1.14 °C higher than pre-industrial.[15]
- Human-induced global warming is responsible for all observed warming within uncertainties (1.14 compared to 1.15 °C).[16]

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

- In 2022, the single-year human-induced global warming was 1.26 °C and warming has been increasing at an unprecedented rate of over 0.2 °C per decade.[17]

5) Reaching a *future* level of global warming is defined as the midpoint of the first 20-year period when average global surface air temperature change exceeds a particular level of global warming based on scenario projections with accelerated rate of warming in the near term.[18]

- The 20-year global average surface temperature could exceed the 1.5 °C guardrail by the early 2030s and 2 °C by 2050 or sooner due to rising emissions, declining particulate air pollution that unmasks existing warming, and natural climate variability (**Figure 1**).[19] There is a 50% probability that 1.5 °C has been crossed once the observed mean for the most recent 11-years reaches 1.43 °C and 90% at 1.43 °C.[20]
- According to the AR6 Synthesis Report, under current policies, global temperatures are on track to reach 3.2 °C [2.2–3.5 °C] by the end of the century; if climate sensitivity or climate feedbacks are higher, warming levels could exceed 4 °C.[21] (A preprint from Hansen *et al.* concludes that the climate may be even more sensitive to climate forcing than previously thought, implying that there may be more warming in the "pipeline" than expected, which "will likely pierce the 1.5°C ceiling in the 2020s and 2°C before 2050," and eventually reach an equilibrium warming of 8–10 °C in later centuries.[22]).

- The concentration of climate pollutants in the atmosphere continues to increase at record rates despite the pandemic and economic slowdown.
    - In 2022, the global average atmospheric concentration of CO_2 was a record 417.06 parts per million ("ppm"). The 2.13 ppm increase between 2021 and 2022 was the 11th consecutive year where the amount of CO_2 increased by more than 2 ppm. The rate of increase in CO_2 over the past 60 years is nearly 100 times faster than previous natural increases, including those that occurred at the end of the last ice age 11,000–17,000 years ago.[23] For comparison, in the 1990s the average increase of CO_2 was 1.5 ppm/year.[24]
    - In September 2021, atmospheric methane concentrations exceeded 1,900 parts per billion (ppb).[25] The annual growth rates set records in 2020 (15 ppb/year) and 2021 (18 ppb/year) for the fastest rates of increase since records started in 1983, more than double the 2007–2019 average (7.3 ppb/year).[26] Recent studies attribute this surge of atmospheric methane concentrations to increasing emissions from wetlands and a reduced capacity of the atmosphere to remove methane.[27] Methane concentrations increased by14 ppb in 2022 to reach an average of 1,912 ppb, more than two and half times pre-industrial levels.[28]
    - N_2O concentrations grew by 1.24 ppb to 335.7 ppb in 2022, representing a 24% increase over pre-industrial levels. The highest growth rates recorded occurred in 2020 and 2021.[29]
    - Today the blanket of climate pollution surrounding the Earth is trapping twice as much heat as it did in 2005, with loss of reflective sea ice and changes in clouds contributing significantly to the extra heat the planet is now retaining.[30]
- Anthropogenic changes to the climate are on track to exceed the natural variability of the past 66 million years and is accelerating a transition characterized by extreme weather events.[31]
- Even at 1.2 °C of observed global warming in 2021–2022,[32] weather extremes are becoming more frequent and more severe.[33] According to AR6 WGI, "[i]t is *virtually certain* that hot extremes (including heatwaves) have become more frequent and more intense across most land regions since the 1950s… with *high confidence* that human-induced climate change is the main driver of these changes."[34]
    - Every year, heatwaves continue to break records all over the world. Given our current emissions trajectory, the probability of extreme record-breaking heatwaves will continue to increase (*see* **Box 2**). UN Secretary-General Guterres recently warned that "the era of global warming has ended" and "the era of global boiling has arrived"—urging immediate action to "turn a year of burning heat into a year of burning ambition."[35]
- The probability of "record-shattering" extreme climate events increases with the rate of near-term warming,[36] while the frequency and intensity of extreme events scale with warming levels.[37]

Box 2. Extreme weather events

Extreme Heat

- July 2023 was likely the warmest month in 120,000 years,[38] breaking global heat records for four days in a row.[39] The "maximum heat like in July 2023 would have been virtually impossible to occur in the U.S./Mexico region and Southern Europe if humans had not warmed the planet by burning fossil fuels."[40]
- The 2021 heatwave in western Canada and the northwest US would have been virtually impossible absent human-induced global warming, and in a 2 °C world, would occur every 5 to 10 years.[41]
- The 2022 record-breaking early season heatwaves in Argentina and Paraguay were made 60 times more likely due to anthropogenic climate change.[42] These heatwaves increased wildfires in Argentina and Paraguay by 283% and 258% at the beginning of 2022.[43]
- In 2022, unprecedented heatwaves affected nearly 2 billion people in India and Pakistan, with scientists noting that "the current climate has changed so significantly that the pre-industrial world becomes a poor basis of comparison."[44]
- By 2053, an "extreme heat belt" affecting over 100 million people is expected to form in the central U.S., where temperatures will exceed 125 °F (~52 °C) at least once a year.[45]

Flooding

- In 2022, the catastrophic flooding that affected 33 million people in Pakistan[46] was very likely made more severe by climate change, increasing rainfall, glacier melt, and extending a La Niña event in the Pacific for a rare third year.[47]

Droughts

- In 2022, Chile entered the 14th year of its megadrought, the longest and most severe drought in the country in over a thousand years.[48]

Storms & Cyclones

- In 2021, Latin America and the Caribbean experienced a higher-than-average number of tropical cyclones that caused about US$ 80 billion in damages to people and infrastructure.[49] This was the sixth year in a row where the Atlantic hurricane season was higher than average.[50]

B. Only a dual assault on CO_2 and super climate pollutants, particularly methane, would make it possible for the world to keep 1.5 °C in sight and stay below 2 °C

- The CO_2 and super climate pollutant strategies are complementary and not exchangeable. Achieving 2050 Net Zero CO_2 targets is essential for stabilizing the climate by the end of the century due to the long lifetime of CO_2 in the atmosphere; but it cannot, by itself, prevent global temperatures from exceeding 1.5 °C above pre-industrial levels, the guardrail beyond which the climate begins to "transition to high risk" of passing irreversible tipping points.[51]
    - The recent AR6 reports confirm that cutting fossil fuel emissions—the main source of CO_2—by decarbonizing the energy system and shifting to clean energy, *in isolation, actually makes global warming worse in the short term*. This is because burning fossil fuels also creates sulfate aerosols, which act to cool the climate. These cooling sulfates fall out of the atmosphere fast, while CO_2 lasts much longer—decades to centuries—, thus leading to relatively higher warming for the first decade or two.[52]

  - The International Energy Agency report, *Credible Pathways to 1.5 °C: Four Pillars for Action in the 2020s*, also recognizes that "tackling non-CO_2 emissions is vital to limiting peak warming. Assuming strong action on CO_2, meeting or exceeding commitments like the Kigali Amendment on HFCs and the Global Methane Pledge, and acting on non-CO_2 emissions from agriculture, could make the difference between a scenario which substantially overshoots 1.5 °C, risking triggering irreversible climate tipping points, and one which does not."[53]
- In addition to zeroing out CO_2 emissions to curb long-term warming, it is essential to slow near-term warming by reducing SLCPs—methane (CH_4), black carbon (BC) soot, tropospheric ozone (O_3), and HFCs. These short-lived pollutants are often referred to as "super climate pollutants" because of their potency and ability to quickly reduce warming. (Nitrous oxide (N_2O) is also a super climate pollutant but is not short-lived.)
- Reducing SLCPs is the only currently known mitigation strategy that can cut the rate of warming in the near-term, slow self-amplifying feedbacks, and avoid or at least delay irreversible tipping points.

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

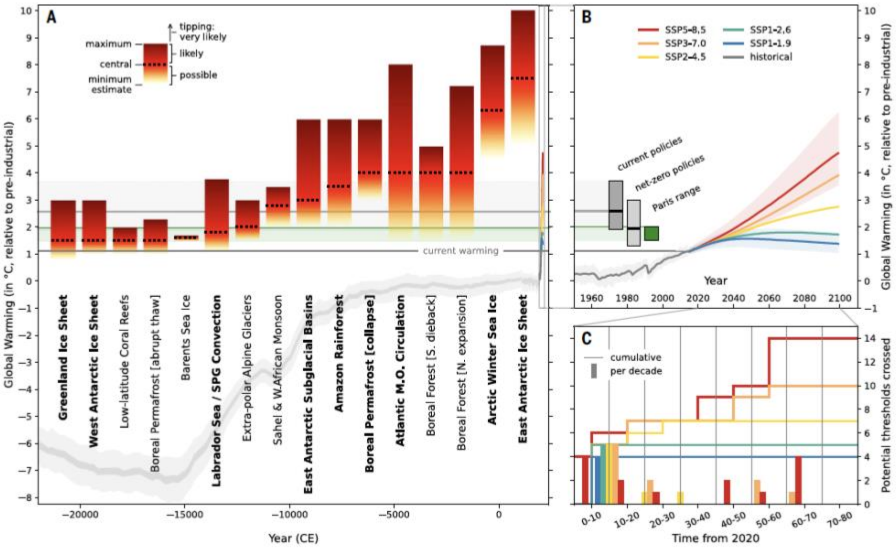
- Addressing the near-term climate emergency requires selecting fast mitigation solutions that: provide the most avoided warming in the shortest period of time over the next decade or two;[54] slow the self-amplifying feedbacks and avoid or at least delay irreversible tipping points;[55] and protect the most vulnerable people and ecosystems from heat, drought, flooding, and other extremes[56] that will dramatically increase in severity and frequency with every increment of additional warming.[57]
  - In addition to cutting CO_2 and super climate pollutants, other fast mitigation strategies must be employed, including protecting sinks.[58] This combined approach is essential for achieving near-term and long-term climate targets.
- Limiting warming to 1.5 °C would prevent most of the tropics from exceeding the combined heat and humidity conditions beyond the survival limit.[59] In contrast, warming of 2.7 °C by the end of the century would leave about a third of the global population outside of the human climate niche (2 to 2.5 billion people), while limiting warming to 1.5 °C would reduce this to less than 5% (0.4 to 0.5 billion people).[60]
- According to AR6 WGIII Summary for Policymakers, keeping the planet livable by limiting warming to 1.5 °C with no or limited overshoot requires reducing human-caused CH_4 emissions by 34% in 2030 and 44% in 2040 relative to modelled 2019 levels, in addition to cutting global CO_2 emissions in half in 2030 and by 80% in 2040, along with deep cuts to other SLCPs and N_2O.[61]
  - AR6 WGIII further finds that "[d]eep GHG [greenhouse gas] emissions reductions by 2030 and 2040, particularly reductions of methane emissions, lower peak warming, reduce the likelihood of overshooting warming limits and lead to less reliance on net negative CO_2 emissions that reverse warming in the latter half of the century…. Due to the short lifetime of CH_4 in the atmosphere, projected deep reduction of CH_4 emissions up until the time of net zero CO_2 in modelled mitigation pathways *effectively reduces peak global warming*. (*high confidence*)." (Emphasis added.)[62]

- In 2023, a group of scientists used the WGI AR6 methods to update the remaining carbon budget for a 50:50 chance of staying below 1.5 °C, 1.7 °C, and 2.0 °C to be 250, 600, and 1150 $GtCO_2$, respectively, noting that "[t]hese estimates assume median reductions in non-CO_2 emissions between 2020–2050 of CH_4 (50 %), N_2O (25 %) and SO_2 (77 %). If these non-CO_2 greenhouse gas emission reductions are not achieved, the [remaining carbon budget] will be smaller."[63]
- While this budget includes some carbon-climate feedbacks,[64] non-linear feedbacks[65] and tipping points are not accounted for directly in the standard calculations, which use a 50% likelihood of meeting target temperature. The uncertainty around when tipping points will be crossed means that such events can only be accounted for using a leaner carbon budget reliant on stricter likelihoods, and even then, accounting is incomplete.[66]
- At current emission levels, the 1.5 °C budget of 250 $GtCO_2$ would run out in mid-2029.[67] The UNFCCC Secretariat's September 2023 "stocktake" of global progress cutting emissions reports that countries are still failing to meet their Paris commitments and the gap to limit warming to 1.5 °C remains high.[68]
- These findings build on the conclusions of the IPCC's 2018 *Special Report on Global Warming of 1.5 °C* that identified the three strategies essential to keep the planet livable:
    i. reaching net zero CO_2 by mid-century;
    ii. making deep cuts to super climate pollutants in the next decades; *and*
    iii. removing up to 1,000 billion tons of CO_2 from the atmosphere by 2100.[69]

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

The "evidence from tipping points alone suggests that we are in a state of planetary emergency: both the risk and urgency of the situation are acute…", according to Tim Lenton and colleagues.[70] The IPCC defines tipping points as "critical thresholds in a system that, when exceeded, can lead to a significant change in the state of the system, often with an understanding that the change is irreversible. An understanding of the sensitivities of tipping points in the physical climate system, as well as in ecosystems and human systems, is essential for understanding the risks associated with different degrees of global warming."[71] Earth system models project a cluster of six such abrupt shifts (not necessarily irreversible) between 1 °C and 1.5 °C of warming and another eleven between 1.5 °C and 2 °C,[72] as confirmed by two IPCC Special Reports.[73] Another recent assessment finds that exceeding 1.5 °C increases the likelihood of triggering or committing to six self-propagating climate tipping points (**Figure 2**).[74]

Figure 2. Abrupt climate changes as global temperatures increase



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

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

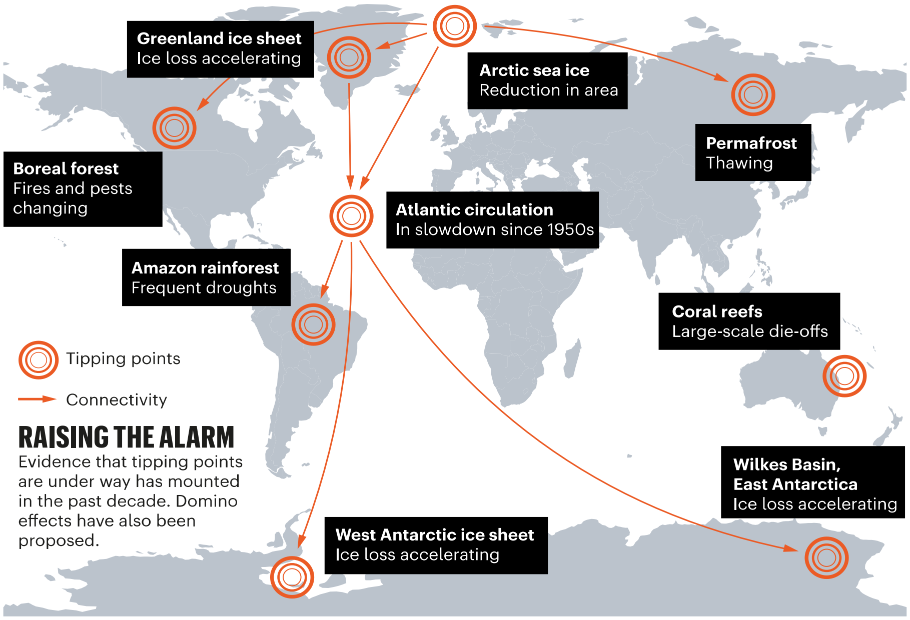
Climate models either ignore or underestimate key feedbacks and tipping point risks.[75] Domino-like interactions among these systems are projected to lower thresholds and increase the risk of triggering a global cascade of tipping points (**Figure 3**).[76] Nor do climate models account for other circumstances that have been shown to lower tipping thresholds, including increasing rates of warming,[77] pressure from multiple drivers, or increased variability in a single driver.[78] Additional as-yet-undiscovered tipping points are possible given the limitations in current models and exclusion of processes such as those related to permafrost and other biogeochemical feedbacks.[79]

Self-amplifying feedbacks, including the loss of Arctic sea ice, are among the most vulnerable links in the chain of climate protection.[80] Climate-driven changes in clouds act as another self-amplifying feedback leading to more warming and higher climate sensitivity.[81] Above 1,200 ppm CO_2, a “stratocumulus cloud deck evaporation” tipping point could raise global warming levels by an additional 8 °C.[82]

Extreme heat and other impacts unleashed by these feedbacks pose systemic risks to human and natural systems, including social, political, financial, and, ultimately, societal collapse. Mapping of projected extreme heat to the Fragile State Index points to significant potential for conflict and vulnerability currently excluded from most economic analyses of social costs of climate pollution.[83]

In addition to potential tipping points in human systems, warming will abruptly shrink the habitable area for thousands of species over the span of a decade or two, likely causing mass extinction for species unable to rapidly migrate or evolve.[84] Even with a 1.5 °C overshoot where the temperature limit is only temporarily breached, some of the impacts will be irreversible, even if warming is later reduced.[85]

Figure 3. Climate tipping points



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

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

The Arctic is critical for climate stabilization, yet it may be the weakest link in the chain of climate protection.[86] The Arctic's sea ice provides a "great white shield" that reflects incoming solar radiation safely back to space.[87] As the extent of the Arctic's reflective sea ice continues to shrink, the amount of heat going into the darker ocean is increasing. This, in turn, causes more ice to melt in a self-amplifying feedback loop[88] and makes sea ice loss unavoidable for decades to come.[89]

The Arctic air temperature is warming at a rate four times faster than the global average,[90] and the last seven years (2016–2022) were the region's seven warmest years on record.[91] Half of the Arctic's September sea ice is already gone,[92] and the rest could disappear within 10 to 15 years.[93]

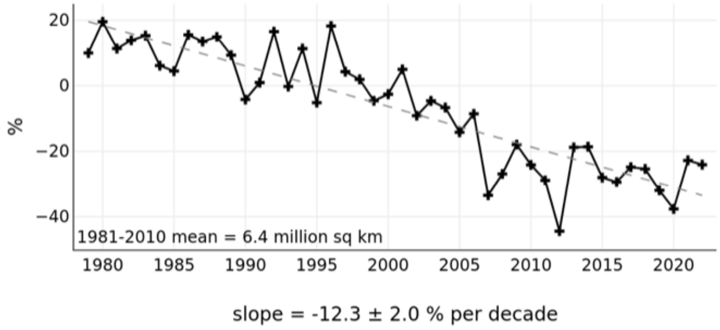
If all of the Arctic sea ice were lost for the sunlit months, which could happen as early as mid-century,[94] it would add the warming equivalent of a trillion tons of CO_2, or 25 years of climate emissions at today's rate.[95] The Arctic's land-based snow and ice is also melting and is expected to add a similar amount of warming.[96] The intrusion of warmer ocean water from both the Atlantic[97] and the Pacific[98] is contributing to Arctic warming and the melting of the sea ice, intensifying the impacts of late summer cyclones and further accelerating sea ice loss.[99]

i. A rapidly warming Arctic

- Arctic air temperature is warming at a rate four times faster than the global average.[100]
  - Arctic mean surface temperatures may rise by up to 10 °C above the 1985–2014 average,[101] and in some regions up to 12 °C above the 1971–2000 average by the end of the century.[102]

  - In 2020, Siberia experienced heat extremes that would have been "almost impossible" without human-caused global warming, including the first 100 °F (~38 ℃) temperature recorded in the Arctic Circle. The record-breaking trends in the Arctic circle continued in the first half of 2021 with ground temperatures reaching 118 °F (~45 ℃).[103]
  - The Arctic's "Last Ice Area," the Wandel Sea, saw unprecedented sea ice loss in August 2020 primarily due to abnormal weather patterns and warmth from the exposed ocean surfaces.[104] Summer sea ice in this area north of Greenland was thought to be more resilient and expected to persist decades longer than the rest of the Arctic,[105] providing a refuge for the region's ice-dependent flora and fauna.[106]
  - Between 1991–2020, surface air temperature in the Barents Sea area experienced record high annual warming of up to 2.7 °C per decade, with the Northern Barents Sea area warming at a rate 5–7 times the global warming averages.[107] During the warmer autumn season, the Northern Barents Sea area reached accelerated warming of up to 4.0 °C per decade between 2001–2020.[108]
- Only half of the summer Arctic sea ice in September remains,[109] with the risk that September will be ice-free within 10 to 15 years.[110] If all the Arctic sea ice were lost for the sunlit months, it would add the warming equivalent of a trillion tons of CO_2.[111]
  - Arctic sea ice reaches its minimum extent or coverage every September. Between 1982–2022, the September minimum extent has decreased significantly, reducing at a rate of approximately 13% per decade.[112] In addition to extent, the thickness and volume of Arctic sea ice have also decreased. During the September minimums of 1982–2020:
    - Arctic sea ice *extent* decreased by 44% (from 7.6 million km^2 in 1982 to 4.3 million km^2 in 2020).[113]
    - Arctic sea ice *thickness* decreased by 48%.[114]
    - Arctic sea ice *volume* decreased by 72%.[115]
    - The 15 Septembers with the least Arctic sea ice extent have all been in the last 15 years; in September 2020, the Arctic sea ice reached the second lowest extent in the satellite record.[116] September 2022 was the 9th lowest ice minimum on record, while September 2021 was the 12th lowest at the time, with one of the lowest recorded levels of multi-year ice.[117]
- The Arctic has lost 95% of its strong multi-year (>4 years old) Arctic sea ice, and is down to only 4.4% of the Arctic Ocean in March 2020; young, first-year ice—which is thinner, more fragile, and more susceptible to decline—now comprises about 70% of the ice pack.[118]
- Land-based snow and ice in the Arctic is also melting and is expected to add a similar amount of warming to the trillion tons of CO_2 from losing the remaining sea ice for all sunlit months.
  - According to Dr. Peter Wadhams:[119] The loss of reflective land-based snow and ice is "of the same magnitude as the sea ice negative anomaly during the same period, and the change in albedo is roughly the same between snow-covered land and snow-free tundra as it is between sea ice and open water.… [T]he similarity of the magnitudes means that snowline retreat and sea ice retreat are each adding about the same amount to global warming."

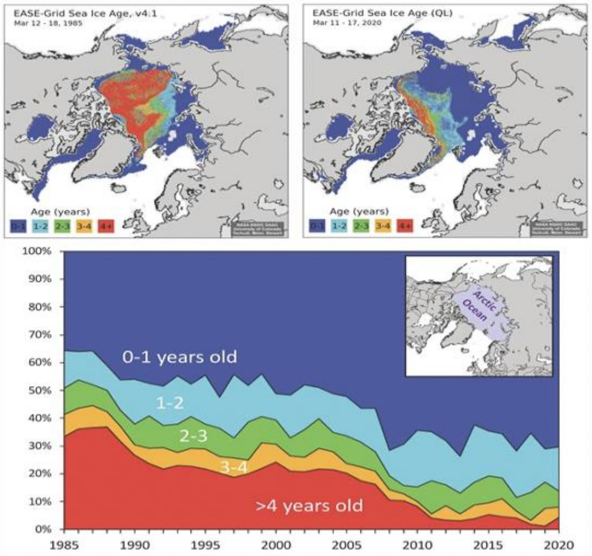
Figure 4. Monthly sea ice extent anomalies Sep 1979–2022



Source: National Snow and Ice Data Center, *Sea Ice Index*, Monthly Sea Ice Extent Anomaly Graph (*last visited* 13 March 2023) ("This graph shows monthly ice extent anomalies plotted as a time series of percent difference between the extent for the month in question and the mean for that month based on the January 1981 to December 2021 data. The anomaly data points are plotted as plus signs and the trend line is plotted with a dashed grey line.").

- Polar ice volume is a strong indicator of changes in the planet's fundamental climate state.[120]
  - Between the periods of 1992–1999 and 2010–2019, the rate of glacier and ice sheet loss increased by a factor of four, and along with glacier mass loss, was the majority contributor to sea level rise between 2006–2018.[121]
  - A study that combined satellite observations with numerical models found that, between 1994 and 2017, glaciers and ice sheets lost 28 trillion tonnes of ice.[122] (One trillion tonnes of ice is equivalent to a cube of ice taller than Mount Everest.[123]) According to the study, "there can be little doubt that the vast majority of Earth's ice loss is a direct consequence of climate warming."[124]

Figure 5. Late winter sea ice in the Arctic



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

- Recent observations in the Antarctic also show a trend of extreme warming and the "retreat, thinning and disintegration" of ice shelves, which form 75% of Antarctica's coastline and act to stabilize the rate of ice flow from the grounded ice sheets.[125]
    - The Antarctic is currently missing a significant amount of ice, currently the size of Greenland (~2 million km^2)—this has a likelihood of happening only once in 7.5 million years, but these extremes are "now virtually certain to continue." [126]
    - In March 2022, the East Antarctic region experienced the most extreme heatwave ever recorded globally, reaching 38.5 °C (69.3 °F) above its average temperature.[127] This is associated with an "atmospheric river" that transports heat and moisture from the subtropics into the Antarctic.[128]
    - Widespread meltwater ponding on the surface of ice shelves contributes to loss; "the collapse of the Larsen-B Ice Shelf was triggered by widespread meltwater ponding on the ice shelf surface where crevasse hydrofractures caused pressure-driven disintegration of the shelf in a matter of days…. If such events become more frequent in a warming climate further incidences of ice shelf disintegration may occur." [129]

ii. Amplification of Arctic warming and sea ice loss—feedbacks and impacts

- Arctic sea ice is declining at an accelerating rate.
    - The rate of decline in Arctic sea ice thickness from 2002 to 2018 may be underestimated by 60–100% in four of the seven marginal seas, according to a recent study using "snow data with more realistic variability and trends."[130]
    - Warmer oceans are also accelerating sea ice loss, with warmer Atlantic[131] and Pacific[132] water transporting "unprecedented quantities of heat" into the Arctic Ocean, further reducing sea ice thickness. The warmer, saltier waters from the Atlantic Ocean are increasingly entering the Arctic in a process called "Atlantification of Arctic Ocean"[133] that is propagating northward. The strength of this warming is likely underestimated in CMIP6 models.[134] (The Coupled Model Intercomparison Phase 6 global climate models were used in AR6.)
    - In the Northern Barents Sea, winter sea ice loss due to warmer waters transporting heat from the Atlantic Ocean is more pronounced. As subsurface water becomes warmer and saltier, it becomes buoyant enough to break through to the surface, and this weakened ocean stratification prevents the formation of sea ice.[135] Sea ice cover and ocean stratification in this region have been linked to abrupt changes during the last ice age.[136]
    - With less sea ice in the Arctic Ocean, ocean waves can grow larger and accelerate ice breakup and retreat;[137] late summer cyclones exacerbate this.[138]
    - Exceptionally high winds in winter of 2020/21 drove multi-year ice into the Beaufort Sea,[139] "where ice increasingly can't survive the summer," resulting in record loss of the Arctic's multi-year ice.[140]
    - Arctic warming also leads to a greater number of cyclones and to more intense cyclones,[141] which further exacerbate Arctic sea ice decline and vice-versa.[142]

iii. We are perilously close to losing our Arctic climate control

- The Arctic could become nearly sea ice-free in September as soon as the 2030s, further reducing its heat-reflecting ability.[143]
    - Dansgaard-Oeschger events during the last ice age were associated with a rapid decline in Arctic sea ice that may have acted as a tipping point leading to changes in oceanic heat circulation accompanied by a 2 to 3 °C rise in near-surface temperature over the Nordic sea.[144]
    - Ice-free conditions over multiple summer months likely occurred during the last interglacial period, providing further support for predictions of ice-free conditions in late summer by 2035.[145]
    - The Barents Sea and Greenland Sea could become ice-free year-round by the end of the century under high emissions scenarios.[146]
- In the extreme case when all Arctic sea ice is lost for the sunlit months, as could happen as early as mid-century,[147] it would add the warming equivalent of 25 years' worth of current emissions—one trillion tons of CO_2—on top of the forcing from the 2.4 trillion tons of CO_2 emitted in the 270 years since the Industrial Revolution.[148]
    - This additional warming would be the equivalent of adding 56 ppm of CO_2 to the current CO_2 concentration.[149]
    - The added forcing in the Arctic would be 21 W/m^2; averaged globally this would equal 0.71 W/m^2 of global forcing,[150] compared to the 2.16 W/m^2 added by anthropogenic emissions of CO_2 since the Industrial Revolution.[151]
    - If all of the cloud cover over the Arctic dissipates along with the loss of all sea ice, the added Arctic warming could be three times as much—the equivalent of three trillion tons of CO_2. In contrast, even if clouds increase to create completely overcast skies over the Arctic, the warming would still add the equivalent of 500 billion tons of CO_2 to the atmosphere.[152]
- Additional factors contribute to further snow and ice loss in the Arctic.
    - Reduced Arctic snow cover is increasing the risk of wildfires, which emit black carbon, another super climate pollutant, while destroying sinks and emitting CO_2;[153] wildfires and permafrost thawing can "act together to expose and transfer permafrost C to the atmosphere very rapidly."[154] In 2021 alone, wildfires in the Arctic emitted 16 million metric tons of carbon.[155]
    - The warming Arctic has also experienced three times more lightning in the last decade,[156] igniting more fires and threatening to accelerate permafrost thaw.[157] Boreal fires which smolder in organic soils and remerge after months, called "zombie fires" or "overwintering fires," emitted about 3.5 million metric tons of carbon between 2002 and 2018.[158]
    - Rapid melting in the Arctic opens up new shipping lanes, which trigger further pollution and warming as increased shipping traffic, oil and gas exploration, and tourism burns heavy fuel oil and emits black carbon.[159] From 2009–2018, shipping activity in the Norwegian Exclusive Economic Zone increased by 42%.[160] Increased Arctic shipping lanes also introduce geopolitical problems and other evolving security risks.[161]

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

As the Arctic continues to warm at four times the global average,[162] it is already starting to thaw the Arctic permafrost in a self-amplifying feedback loop that could release 110 to more than 550 Gt CO_2 this century,[163] rivaling the cumulative emissions from the United States at its current rate (approximately 400 GtCO_2 based on current emissions of about 5 GtCO_2 per year).[164]

- Permafrost contains nearly twice the amount of carbon than is already in the atmosphere.[165] As it thaws it releases ancient stores of CO_2, methane,[166] and N_2O[167] (which also destroys stratospheric ozone).
- Yet more than 80% of IPCC models do not include climate emissions from permafrost thaw.[168]
- Arctic permafrost at high latitudes has warmed at a rate of 1 °C per decade since the 1980s.[169] AR6 WGI calculates that for each °C of global warming at 2100, the permafrost feedback could release 66 GtCO_2 (11 to 150) and 10 GtCO_2e (2.6 to 27) of methane, in addition to N_2O, which most estimates do not account for.[170]
- In addition, up to 20% of the permafrost area accounting for half of permafrost carbon could experience abrupt local thaw events, such as the deep sinkholes observed in the Beaufort Sea.[171]
  - These abrupt thaw events could cumulatively emit up to nearly 11 Gt carbon in the form of CO_2 (40 Gt CO_2) and 6.8 Gt carbon in the form of methane (9 Gt CH_4) by 2100, in addition to the 92 Gt carbon that could be released by gradual thaw over this period under a high-emission scenario.[172]
  - Models that consider only gradual thaw underestimate permafrost carbon emissions by 40% through 2300.[173]
  - Some of the emissions from thawing permafrost are expected to be offset by the expanded growth of biomass, but only if human emissions are curbed.[174]
- In addition to accelerating soil carbon feedbacks due to permafrost thaw, heatwaves in the Siberian Arctic (such as those in 2020 that peaked at 6 °C above normal temperatures) may be causing “surprise” fossil methane gas to leak from rock formations.[175]
- The increasing Arctic wildfires are accelerating permafrost thaw.[176]
  - “Fire-induced permafrost thaw may be a dominant source of Arctic carbon emissions during the coming decades.”[177]
- Thawing permafrost also impairs human settlements and health.
  - About 3.3 million people, 42% of settlements, and 70% of current infrastructure in the permafrost is at risk of severe damage due to permafrost thaw by 2050, including 45% of oil and gas production fields in the Russian Arctic.[178] Damage to Russian infrastructure alone due to permafrost thaw could cost US$ 69 billion by 2050.[179]
  - Thousands of industrial sites in the Arctic risk mobilization of legacy contamination due to warming and thawing permafrost, which contain uncharacterized pathogens.[180]

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

Another risk is that warming ocean waters will destabilize seabed methane hydrates.[181] Such destabilization likely occurred off the coast of Guinea 125,000 years ago during the previous interglacial period, with ice core records suggesting that a sufficient amount of methane was released to the atmosphere to affect CO_2 and methane concentrations.[182] With a rapidly warming Arctic, the shallow seabed of the East Siberian Arctic Shelf poses a significant risk due to its potential to speed up other global warming impacts.[183] Although there is debate on the rate of potential release,[184] the rate of methane release in the Chukchi Sea was higher in 2010s compared to 1990s.[185] Release of land-based methane hydrates as glaciers recede could further amplify the permafrost feedback.[186]

- Measurements in October 2020 by an international expedition on a Russian research vessel showed elevated methane release from the Arctic Shelf, according to Jonathan Watts in *The Guardian*.[187] The story quotes Swedish scientist Örjan Gustafsson of Stockholm University, stating that the "East Siberian slope methane hydrate system has been perturbed and the process will be ongoing." Analysis of elevated methane measured in the area in 2014 suggests a fossil methane source beneath the seabed that "may be more eruptive in nature."[188]
- 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.[189]

E. The approaching ice sheet tipping points

Several climate tipping points are at risk if warming exceeds 1.5 °C for more than several decades, with the Greenland Ice Sheet and West Antarctic Ice Sheet both already showing signs of approaching tipping thresholds estimated around 1.5–2 °C.[190] Once triggered, significant ice loss is irreversible even if CO_2 removal strategies are successful.[191] In 2021, Greenland reached record low levels of ice mass, with glaciers losing 31% more snow and ice per year than just 15 years ago.[192] Antarctic sea ice extent reached a satellite-era record low in February 2022.[193]

The melting Greenland Ice Sheet is already the largest single contributor to the rate of global sea level rise,[194] and is expected to lose 110 trillion tons of ice by the end of the century, which would raise global sea levels by nearly a foot (27 cm).[195] Recent observations show that the rate of retreat was as high as 610 m per day during the last interglacial period, and current levels of ocean-driven melting can trigger 100 m of ice sheet loss each day.[196] AR6 WGI was unable to exclude the possibility of sea level rise of up to 7.5 feet (2.3 m) by 2100 due to uncertainties in ice sheet processes.[197]

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

- Early warning signs suggest that the Greenland Ice Sheet is close to a tipping point.[198] Currently, the best estimate of the threshold for irreversible melting of the Greenland Ice Sheet is around 1.6 °C (0.8–3.2 °C).[199]

  - In the past two decades, the melt rate across Greenland increased 250–575%,[200] and the ice discharge from the Greenland Ice Sheet substantially increased; this will likely persist in the coming years.[201] On 28 July 2021, Greenland experienced a massive melt event that alone would be enough to cover the state of Florida by two inches of water.[202]
  - If all of Greenland melted, it would contribute 5–7 meters of sea level rise. While fully melting the Greenland Ice Sheet would take millennia, the rate of future melt, and hence rate of sea level rise, depends "strongly on the magnitude and duration of the temperature overshoot."[203] The melting Greenland Ice Sheet is already the largest single contributor to the rate of global sea level rise.[204]
  - On 14 August 2021, rainfall occurred at the highest point on the Greenland Ice Sheet, which has never been recorded before at that location (72.58°N 38.46°W).[205]
- A recent analysis calculated that 3.3% of the Greenland Ice Sheet (equivalent to 110 trillion tons of ice) will inevitably melt by the end of the century regardless of any climate emissions scenario, triggering at least 27.4 cm (10.8 in) of global sea level rise, and reaching as much as 78.2 cm (30.8 in).[206]

ii. The Atlantic Meridional Overturning Circulation is weakening

- The melting of Greenland also contributes to the weakening of the Atlantic Meridional Overturning Circulation (AMOC), which has reached a critical "overturning" stage; the observational data suggest that the AMOC has been weakening since 2008, "this decline may be associated with an almost complete loss of stability of the AMOC over the course of the last century,[207] and that the AMOC could be close to a critical transition to its weak circulation mode."[208]
  - According to AR6 WGI, it is "very likely" that the AMOC will weaken in the 21st century, with *medium confidence* that it will not collapse by 2100.[209] However, current models may be biased in favor of a stable AMOC.[210] A recent study estimates AMOC collapse as early as the 2050s, with a 95% confidence range between 2025–2095.[211]
  - Higher rates of warming could trigger AMOC tipping even before a projected warming threshold is reached, increasing the likelihood and advancing the onset of AMOC collapse.[212]
  - The collapse of AMOC would shift weather patterns around the world, with potentially devastating consequences.[213]
  - It also would lead to faster sea level rise along parts of the Eastern United States and Europe, stronger hurricanes in the Southeastern United States, and reduced rainfall across the Sahel.[214] If the sea level along U.S. coasts increased by 10–12 inches by 2050, the occurrence of destructive floods would increase five-fold.[215]
- In addition to the impacts on AMOC in the northern hemisphere, in the southern hemisphere, meltwater from the Antarctic ice sheets can weaken the southern overturning circulation by 40% and the AMOC by 19% under a high-emission scenario by 2050, with climate impacts that could last for centuries.[216]

Box 3. The Atlantic Meridional Overturning Circulation

The National Oceanic and Atmospheric Administration explains the Atlantic Meridional Overturning Circulation (AMOC) as:[217]

"The ocean's water is constantly circulated by currents. Tidal currents occur close to shore and are influenced by the sun and moon. Surface currents are influenced by the wind. However, other, much slower currents that occur from the surface to the seafloor are driven by changes in the saltiness and ocean temperature, a process called thermohaline circulation. These currents are carried in a large "global conveyor belt," which includes the AMOC.

The AMOC circulates water from north to south and back in a long cycle within the Atlantic Ocean. This circulation brings warmth to various parts of the globe and also carries nutrients necessary to sustain ocean life.

The circulation process begins as warm water near the surface moves toward the poles (such as the Gulf Stream in the North Atlantic), where it cools and forms sea ice. As this ice forms, salt is left behind in the ocean water. Due to the large amount of salt in the water, it becomes denser, sinks down, and is carried southwards in the depths below. Eventually, the water gets pulled back up towards the surface and warms up in a process called upwelling, completing the cycle.

The entire circulation cycle of the AMOC, and the global conveyor belt, is quite slow. It takes an estimated 1,000 years for a parcel (any given cubic meter) of water to complete its journey along the belt. Even though the whole process is slow on its own, there is some evidence that the AMOC is slowing down further.…

As our climate continues to change, is there a possibility that the AMOC will slow down, or come to a complete stop? While research shows it is weakening over the past century, whether or not it will continue to slow or stop circulating completely remains uncertain. If the AMOC does continue to slow down, however, it could have far-reaching climate impacts. For example, if the planet continues to warm, freshwater from melting ice at the poles would shift the rain belt in South Africa, causing droughts for millions of people. It would also cause sea level rise across the U.S. East Coast."

iii. The West Antarctic Ice Sheet is destabilizing

- In West Antarctica, losing the Thwaites glacier, which is currently the size of Florida or Britain, could raise sea levels by over two feet (65 cm).[218] Once the Thwaites glacier retreats past a ridge 50 km upstream, the self-amplifying retreat would "become unstoppable."[219]
    - A 2022 study warned that the Thwaites glacier has melted faster than previously observed and that a similar pace of rapid melt could occur in the future.[220]
    - The Thwaites glacier is already contributing to 4% of sea level rise.[221] In the last 20 years, the glacier has lost more than 1,000 billion tons of ice and is continuing to lose ice at a rapidly increasing rate.[222]
    - One glaciologist found that the ice shelf buttressing the Thwaites glacier could collapse in as little as five years due to massive fractures caused by warmer ocean water that weakens the ice shelf, thereby setting off a "chain-reaction" that could eventually add 2 to 10 feet of sea level rise over centuries.[223]

  - Thinning of the Thwaites glacier appears to have accelerated since 2009.[224] The ice-front of the glacier is also retreating due to ice calving, which can trigger further melting and instability; a catastrophic calving event would lead to greater, more immediate sea-level rise than that caused by ice-shelf thinning alone.[225]

F. The ocean is a heat battery

Compounding the risk from self-amplifying feedbacks and tipping points, warming will continue well after emissions stop; about 93% of the energy imbalance accumulates in the oceans as increased heat,[226] which will return to the atmosphere on a timescale of decades to centuries after emissions stop.[227] By 2003–2018, the rate of ocean warming increased tenfold from 1958–1973 levels.[228] The highest ocean heat content in historical records was measured in 2022.[229] As reported in AR6 WGI:

> "It is *virtually certain* that the global ocean has warmed since at least 1971, representing about 90% of the increase in the global energy inventory… and is currently warming faster than at any other time since at least the last deglacial transition (*medium confidence*). It is *extremely likely* that human influence was the main driver of ocean warming. Ocean warming will continue over the 21st century (*virtually certain*)… [and] is irreversible over centuries to millennia (*medium confidence*)."[230]

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

Decarbonizing the energy system and achieving net-zero emissions is critical for stabilizing the climate and keeping temperatures below 1.5 °C by the end of this century. However, stopping burning fossil fuels, like coal and diesel, also means cutting co-emitted cooling aerosols. These cooling aerosols fall out of the atmosphere in days to months, which offsets reductions in warming from decarbonization until around 2050 and likely even accelerates warming over the first decade or more.[231] As stated by climate scientist and IPCC author Joeri Rogelj: "The removal of air pollution, either through air quality measures or because combustion processes are phased out to get rid of CO_2, will result in an increase in the resulting rate of warming.… The only measures that can counteract this increased rate of warming over the next decades are methane reductions."[232]

- Air pollution that is co-emitted with CO_2 when sulfur-containing coal and oil are burned results in particles that reflect sunlight. These co-emitted sulfate cooling aerosols currently "mask" warming of about 0.5 °C; and while the accumulated CO_2 in the atmosphere will continue to cause warming for decades to centuries, the cooling aerosols fall out of the atmosphere within days to months once they are stopped at the source, unmasking more of the existing warming.[233]
  - The temporary cooling effects of aerosols have been demonstrated in the past. The 1991 Mount Pinatubo eruption injected 15 million tons of sulfur dioxide (SO_2) into the atmosphere, temporarily cooling the planet by 0.5 °C for nearly two years.[234]
  - Further evidence of the potential speed and magnitude of this unmasking effect is provided by the natural experiment of the pandemic shutdown, which abruptly reduced fossil fuel burning and resulted in temporary unmasking over South Asia that increased local radiative forcing by 1.4 Wm^{-2}, equivalent to three-fourths of radiative forcing from CO_2.[235]

    - A recent assessment of satellites and other evidence finds that the net effect of anthropogenic aerosol forcing has changed from negative (cooling) to positive (warming) over the last two decades, contributing the equivalent of 15–50% of the increase in forcing due to CO_2 over the same time period, and concluding that "[t]his signal will most likely continue in the future, increasing the urgency for strong measures on reducing greenhouse gas emissions… ."[236]
- A 2017 study calculated that fast cuts to CO_2 could avoid 0.1 °C of warming by 2050 and up to 1.6 °C by 2100,[237] not counting the extra warming from unmasking.[238]
    - This would require CO_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.[239]
    - If CO_2 emissions were to peak in 2020 and decline at 5.5% per year until carbon neutrality is reached (around mid-century) then level off, this extreme scenario could avoid 0.3 °C of warming by 2050 and up to 1.9 °C by 2100, although unmasking of the cooling aerosol would still lead to net warming in the near term.[240]
    - A 2019 study calculated near-term warming within the next two decades of 0.02–0.10 °C due to cuts to fossil fuel CO_2 emissions and associated reductions in cooling aerosols.[241]

Figure 6. Temperature response of mitigation strategies focusing only on CO_2 (decarbonization alone) compared to decarbonization plus measures targeting super climate pollutants

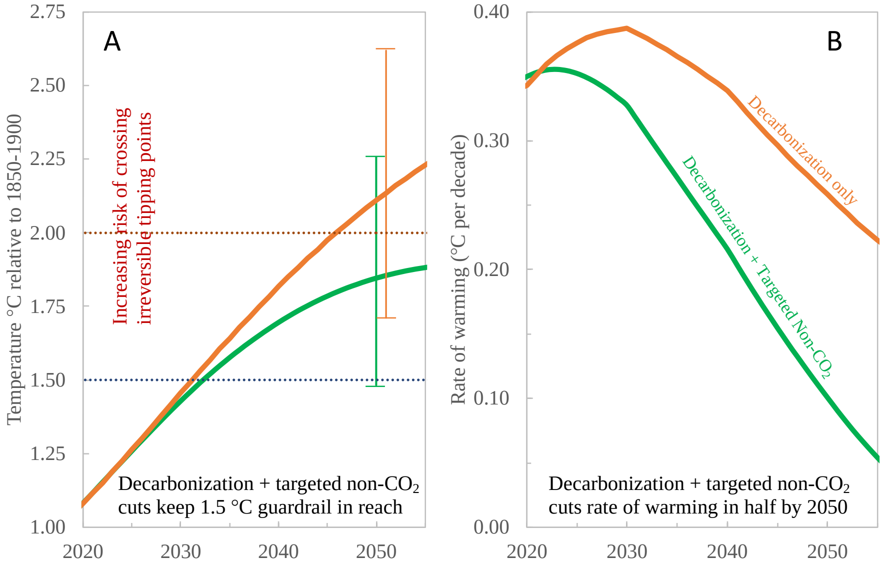


Figure A: Global Surface Air Temperature relative to pre-industrial for two scenarios: decarbonization alone (orange) and decarbonization plus measures targeting non-CO_2 pollutants including methane, hydrofluorocarbon refrigerants, black carbon soot, ground-level ozone smog, as well as nitrous oxide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

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

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

Aggressive mitigation of short-lived climate pollutants (SLCPs)—methane, tropospheric ozone, black carbon, and HFCs—is critical for near- and long-term climate protection. These SLCPs are known as "super climate pollutants." AR6 WGI included a chapter on short-lived climate pollutants for the first time, and reported that "[s]ustained methane mitigation, wherever it occurs, stands out as an option that combines near- and long-term gains on surface temperature (*high confidence*) and leads to air quality benefits by reducing surface ozone levels globally (*high confidence*). Additional CH_4 and BC mitigation would contribute to offsetting the additional warming associated with SO_2 reductions that would accompany decarbonization (*high confidence*)."[242] The AR6 Synthesis Report further affirmed that "[s]trong, rapid and sustained reductions in methane emissions can limit near-term warming and improve air quality by reducing global surface ozone. (*high confidence*)"[243]

- Cutting SLCPs is the only plausible way to limit warming due to unmasking of cooling aerosols over the next 20 years.[244]
- Accounting for the co-emission of cooling aerosol from fossil fuel burning, a 2022 study found that strategies focusing exclusively on reducing fossil fuel emissions could result in "weak, near-term warming" which could potentially cause temperatures to exceed the 1.5 °C level by 2035 and the 2 °C level by 2050. When accounting for unmasking, policies targeting CO_2 through phasing out fossil fuel use would avoid net warming of about 0.07 °C by 2050 compared with 0.26 °C avoided net warming from measures targeting SLCPs.[245] Further, the dual strategy that pairs CO_2-focused decarbonization with rapid reductions to the non-CO_2 pollutants, especially the SLCPs, would result in net avoided warming by 2050 of about 0.34 °C (0.07 °C plus 0.26 °C with rounding), which is more than four times larger than the net effect of decarbonization alone (0.07 °C C). This would enable the world to stay well below the 2 °C limit, and significantly improve the chance of remaining below the 1.5 °C guardrail.[246]
- Cutting CO_2 from fossil fuel emissions reduces warming 0.1 to 0.2 °C by 2050, in contrast to fast cuts to SLCPs which could avoid up to 0.6 °C of warming by 2050, and up to 1.2 °C by 2100.[247] (This does not account for the unmasking as sulfates co-emitted with burning fossil fuels are reduced.) Fast cuts to SLCPs could reduce projected warming in the Arctic by two-thirds, the rate of global warming by half, and avoid or at least delaying self-amplifying feedbacks and irreversible tipping points.[248] Reducing HFCs through the 2016 Kigali Amendment to the Montreal Protocol will account for nearly 0.1 °C of the avoided warming by 2050.[249]
    - AR6 WGIII found that limiting warming to 1.5 °C with no or limited overshoot requires deep cuts to SLCPs, in particular reducing methane emissions by 34% in 2030 and 44% in 2040 relative to 2019 models and reductions of HFC emissions by 85% by 2050 relative to 2019.[250] This re-affirmed the conclusion by the IPCC's *Special Report on Global Warming of 1.5 °C* that cutting SLCPs is essential for staying below 1.5 °C.[251]
    - Similarly, the warning of the climate emergency issued in November 2019 from 11,000 scientists also emphasizes the importance of cutting SLCPs:

> "We need to promptly reduce the emissions of short-lived climate pollutants, including methane (figure 2b), black carbon (soot), and hydrofluorocarbons (HFCs). Doing this could slow climate feedback loops and potentially reduce the short-term warming trend by more than 50% over the next few decades while saving millions of lives and increasing crop yields due to reduced air pollution (Shindell *et al.* 2017[252]). The 2016 Kigali amendment to phase down HFCs is welcomed."[253]

- In their 2021 update, the scientists stress the urgency of "massive-scale climate action" due to growing severity of impacts and risks from "the many reinforcing feedback loops and potential tipping points" and call for "immediate and drastic reductions in dangerous short-lived greenhouse gases, especially methane."[254]

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

Reducing the risks associated with accelerating warming requires mitigation strategies, like cutting methane emissions, that can slow warming in the near term. Assessing how strategies affect near-term warming requires considering individual emissions by pollutant in units of mass, as required under United Nations Framework Convention on Climate Change (UNFCCC) reporting guidelines and recommended by climate scientists.[255] It also requires accounting for co-emissions by source, since policies act on sources, not on individual pollutants.

An ideal option for assessing temperature impact is to convert emissions by source in terms of pollutant and co-emissions to temperature impacts using tools such as the Assessment of Environmental and Societal Benefits of Methane Reductions Tool or the CCAC Temperature Pathway Tool. Alternatively, using the 20-year global warming potential (GWP$_{20}$) better captures near-term warming impact than the 100-year GWP, in addition to being more aligned with meeting the 1.5 °C target.[256] While the UNFCCC currently requires using the GWP$_{100}$ metric when reporting aggregated emissions or removals, which systematically undervalues the climate impact of methane, reporting Parties may use other metrics in addition, such as GWP$_{20}$ or absolute temperature potentials.[257] Indeed, using GWP$_{100}$ alone systematically underestimates the importance of methane emissions and "can lead to suboptimal policies and priorities by misleading climate actors from the top levels of governments (e.g., U.S. NDC) to grassroots organizations."[258]

AR6 has updated the metrics for methane as follows: GWP$_{20}$ is 81.2 and GWP$_{100}$ is 27.9.[259] **Table 1** below summarizes GWP values for methane from IPCC reports.

Table 1. GWP values for methane from IPCC reports

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

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

Most aggregation metrics are designed for comparison with long-lived CO_2. Metrics such as CO_2-equivalence in terms of GWP and GWP* are based on mathematical relationships that are intended to make short-lived pollutants like methane comparable to the longer-term warming impact of CO_2 emissions.[260] These aggregate metrics generally ignore co-emitted pollutants with significant near-term climate impacts such as cooling aerosols. The GWP* metric seeks to account for the shorter lifetime of methane by differentiating historical emissions from changes in the rate of emissions.[261] One criticism of this approach is that it essentially "grandfathers" historical emissions, so when applied at the scale of regional or individual methane emitters, sources with high historical emissions can claim negative GWP* by reducing their rate of emissions. This is the case even if their emissions in a given year are equivalent to a new source with no historical emissions. This has led to the misuse of these metrics to claim that some sectors with large historical emissions and stable or decreasing current rates of emissions have contributed less to global warming.[262]

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

A. Methane (CH_4)

According to AR6 WG1, methane pollution has already caused 0.51 °C of warming of the total observed warming for 2019 of 1.06 °C (0.88–1.21 °C).[263] Warming caused by methane will continue to increase as anthropogenic methane emissions, which are responsible for nearly 45% of current net warming,[264] continue to increase. Recent studies identified feedback mechanisms from natural sources and sinks, which accelerated the growth of methane in 2020 and 2021, including increased emissions from wetlands and reduced capacity of the atmosphere to remove methane.[265] Methane also is an indirect climate forcer forcer as it is a precursor to other GHGs, notably tropospheric ozone; it also reduces the formation of cooling sulfate aerosols by acting as a sink for the hydroxy radical.[266]

As noted by the Biden White House, "Methane is a potent greenhouse gas and, according to the latest IPCC report, accounts for about half of the 1.0 degree Celsius net rise in global average temperature since the pre-industrial era."[267] This follows the statement by then President Barack Obama at COP26 that "curbing methane emissions is currently the single fastest and most effective way to limit warming."[268]

Global Methane Assessment

- Cutting methane emissions is the biggest and fastest strategy for slowing warming and keeping 1.5 °C within reach.[269] A *Global Methane Assessment* (GMA) from the Climate and Clean Air Coalition (CCAC) and United Nations Environment Programme (UNEP) led by Dr. Drew Shindell concludes that available mitigation measures could reduce human-caused methane emissions by 45% by 2030 and avoid nearly 0.3 °C of warming by the 2040s.[270]
  - This would prevent 255,000 premature deaths (not including additional benefits of preventing approximately 200,000 premature ozone-related deaths), 775,000 asthma-related hospital visits, 73 billion hours of lost labour from extreme heat, and 26 million tonnes of crop losses globally (annual value beginning in 2030)).[271] Each tonne of methane reduced generates US $4,300 in health, productivity, and other benefits.[272] In addition, methane mitigation strategies provide further cost reductions and efficiency gains in the private sector, create jobs, and stimulate technological innovation.
  - Roughly 60% of available targeted measures have low mitigation costs (defined as less than US $21 per tonne of CO_2e for GWP_{100} and US $7 per tonne of CO_2e for GWP_{20}), and just over 50% of those have negative costs.
  - In the IEA net zero emissions by 2050 scenario, total methane emissions from human activity are reduced by 45% and the energy sector by 75% between 2020 and 2030, at a cost of less than 3% of net income from oil and gas in 2022.[273]

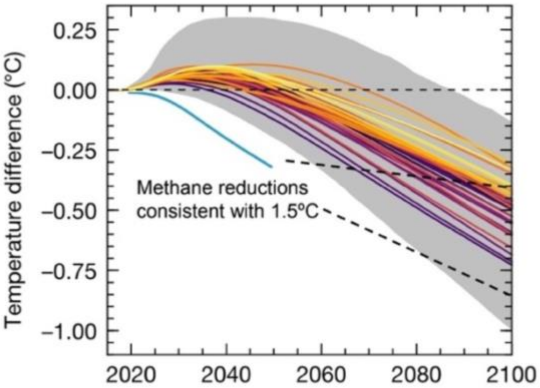
Table 2. Methane mitigation potential in 2030 by sector in MtCH₄/yr and Mt/yr of CO₂e

	Mt CH_4/yr	**Mt CO_2e/yr [GWP_{100}]**	**Mt CO_2e/yr [GWP_{20}]**
Oil & gas	29–57	812–1,596	2,436–4,788
Waste	29–36	812–1,008	2,436–3,024
Agriculture	10–51	280–1,428	2,840–4,284
Coal	12–25	336–700	1,008–2,100

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

- As the GMA notes, "any action taken to reduce emissions will have an immediate pay off for climate in addition to the current and near-future human health and agricultural production.… Indeed, the expectation that a reduction in emissions will yield quick results, in the order of a decade, is confirmed and emphasizes the importance of methane."[274]
- Fast action to pursue all available methane mitigation measures now could slow the global rate of warming by 30% by mid-century.[275] This is consistent with the 2011 UNEP/WMO Assessment showing that fully implementing measures targeting methane and black carbon could halve the rate of global warming and reduce Arctic warming by two-thirds.[276]
    - Strategies to cut methane emissions achieve 60% more avoided warming in the Arctic than the global average, with the potential to avoid 0.5 °C by 2050.[277]
    - Rapid reductions in methane emissions also reduces the risk of losing all of the reflective summer Arctic sea ice.[278]
- Methane mitigation before 2030, along with stringent CO_2 mitigation, can keep global warming well below 2 °C over the next 300 years.[279]
    - Every 10-year delay in methane mitigation after 2040 would cause further peak warming of around 0.1 °C, and would further amplify surface air temperature levels due to biogeochemical feedbacks.[280]
- AR6 WGII and WGIII confirm the findings of the GMA that "[s]ustained methane mitigation, wherever it occurs, stands out as an option that combines near- and long-term gains on surface temperature (*high confidence*) and leads to air quality benefits by reducing surface ozone levels globally (*high confidence*)." Measures specifically targeting methane are essential, as broader decarbonization measures can only achieve 30% of the needed reductions.[281]
    - The most recent report on climate solutions, AR6 WGIII, reinforces the conclusion that deep and rapid cuts to methane emissions are essential to limiting warming in the near-term and shaving peak warming from overshooting 1.5 °C.[282] Limiting warming to 1.5 °C with little or no overshoot requires reducing emissions by 34% below 2019 levels in 2030 and 44% below 2019 levels in 2040.[283]

Figure 7. Methane reductions compared to global mean surface temperature responses to changes in fossil-fuel-related emissions (CO_2 + SO_2)



Source: Shindell D. (25 May 2021) *Benefits and Costs of Methane Mitigation*, Presentation at the CCAC Working Group Meeting. *Updating* Figure 3d from Shindell D. & Smith C. J. (2019) *Climate and air-quality benefits of a realistic phase-out of fossil fuels*, Nature 573: 408–411. *See also* United Nations Environment Programme & Climate & Clean Air Coalition (2021) Global Methane Assessment: *Benefits and Costs of Mitigating Methane Emissions*.

Mitigation and Removal

- Anthropogenic emissions, which make up 60% of total global methane emissions,[284] come primarily from three sectors: energy production (~35%), agriculture (~40%), and waste (~20%).[285] Currently available mitigation measures could reduce emissions from these major sectors by about 180 million metric tonnes of methane per year ($MtCH_4$/yr), approximately 45%, by 2030.[286]
- Specific measures to reduce methane emissions include:
    - Strengthening methane mitigation policies by implementing readily available technologies, laws, and governance structures to their fullest, and considering ways to expand methane mitigation through other available avenues;[287]
    - Reducing leaks[288] and venting[289] in the oil and gas sector. The Clean Air Task Force states that prohibiting venting of natural gas can reduce emissions by 95%;[290]
    - Eliminating flaring from oil and gas operations, while shifting to clean energy.[291]
    - Improving feeding and manure management on farms. In the U.S., this could cut emissions from manure by as much as 70% and emissions from enteric fermentation by 30%;[292]
    - Eliminating gas in new construction and phasing out leaky gas stoves;[293]
    - Upgrading solid waste and wastewater treatment;[294] and
    - Reducing food waste, diverting organic waste from landfills, and improving landfill management, which could reduce landfill emissions in the U.S. by 50% by 2030 and help close the dietary nutrient gap and improve global food security.[295]
- There is research underway on the best approach for removing atmospheric methane.[296] This is especially important, as 35–50% of methane emissions are from natural sources.[297] Methane removal is discussed further in **Section 5C**.
    - A modelling study by a Stanford University-led team calculates that removing around three years' worth of human-caused methane emissions would reduce warming by 0.21 °C. Further, removing one year's worth of methane emissions would reduce transient warming almost four times more than removing one year's worth of CO_2 emissions (0.075 °C for methane compared to 0.02 °C for CO_2).[298]
    - The U.S. National Academies of Sciences, Engineering, and Medicine is developing a research agenda for methane removal.[299]

Global Methane Pledge

- The Global Methane Pledge was launched at COP26 in November 2021.[300] Initially announced by the United States and the European Union at the Major Economies Forum on Energy and Climate hosted by President Biden on 17 September 2021,[301] the voluntary *Pledge* commits governments to a collective goal of reducing global methane emissions by *at least* 30% below 2020 levels by 2030 and moving towards using the highest-tier IPCC good practice inventory methodologies to quantify methane emissions, with a particular focus on high emission sources. As of February 2023, 150 countries including the EU have joined the *Pledge*,[302] representing approximately 70% of the global economy and nearly half of anthropogenic emissions.[303] Philanthropic organizations pledged $328 million to support methane reduction efforts,[304] most of which is being distributed through the Global Methane Hub.[305]

  - Successful implementation of the *Pledge* would reduce warming by at least 0.2 °C by 2050,[306] and would keep the planet on a pathway consistent with staying within 1.5 °C.[307] This reduction is roughly equivalent to a reduction of 35% below projected 2030 levels. Deploying all available and additional measures, as described in the GMA, could lead to a 45% reduction below 2030 levels to achieve nearly 0.3 °C in avoided warming by the 2040s.[308]
  - Implementing the *Pledge* would provide additional benefits, including preventing ~200,000 premature ozone-related deaths, avoiding ~580 million tons of yield losses of staple crops like rice and maize annually, avoiding ~US$ 500 billion annually in losses due to non-mortality health impacts, and impacts on forestry and agriculture, and avoiding ~1,600 billion hours of work lost annually due to heat exposure.[309] Nearly 85% of targeted measures have benefits that outweigh net costs.[310]
- In June 2022, the U.S., EU, and 11 other countries launched the Global Methane Pledge Energy Pathway, which includes US$ 59 million in funding to support methane reductions in the oil and gas sector.[311] The funding includes US$ 4 million to support the World Bank Global Gas Flaring Reduction Partnership, US$ 5.5 million to support the Global Methane Initiative, up to US$ 9.5 million from the UNEP International Methane Emissions Observatory to support scientific assessments of methane emissions and mitigation potential, and up to US$ 40 million annually from the philanthropic Global Methane Hub to support methane mitigation in the fossil energy sector.
- The 2022 U.S. Inflation Reduction Act allocates US$ 369 billion for climate and clean energy policies, including ~US$ 20 billion in incentives to reduce greenhouse gas emissions including methane from the agriculture sector,[312] and US$ 1.55 billion for reducing methane emissions from the oil and gas sector through the Methane Emissions Reduction Program[313] and a fee on methane leaks.[314] This Act is estimated to reduce U.S. GHG emissions by 40% below 2005 levels by 2030.[315]
- In November 2022, the U.S. and EU launched the *Pledge*'s Food and Agriculture Pathway and Waste Pathway to advance methane mitigation in the agriculture and waste sectors. [316] The Food and Agriculture Pathway will leverage up to US$ 400 million to help smallholder farmers transition dairy systems to lower emission, climate-resilient pathways[317] and raise US$ 70 million for a new Enteric Methane Research and Development Accelerator.[318]

IGSD's (2022) *Primer on Cutting Methane: The Best Strategy for Slowing Warming in the Decade to 2030* provides further information on the science of methane mitigation and why action is urgent; current and emerging mitigation opportunities by sector; national, regional, and international efforts that can inform emergency global action on methane; and financing initiatives to secure support for fast methane reduction.

B. Tropospheric ozone (O_3)

Tropospheric ozone is a local air pollutant and a significant GHG. Ozone is not directly emitted but is a product of atmospheric reactions with precursor pollutants, notably methane and other volatile organic compounds and nitrogen oxides (NO_x). In addition to contributing to warming, it is responsible for millions of premature deaths,[319] billions of dollars' worth of crop losses annually,[320] and weakening of carbon sinks.[321]

Mitigation

- Methane contributes 35% to today's tropospheric ozone burden, and reducing it reduces tropospheric ozone levels[322] and improves air quality.[323] Methane is likely to play a greater role in tropospheric ozone formation as emissions of other precursors are reduced by air pollution controls.[324]
- Methane is the last remaining major ozone precursor not explicitly controlled under the 1999 Gothenburg Protocol to Abate Acidification, Eutrophication, and Ground-Level Ozone to the UNECE Convention on Long-Range Transboundary Air Pollution.[325]

C. Black carbon

Black carbon and tropospheric ozone are local air pollutants and are typically addressed under national or regional air pollution laws, as well as through the voluntary programs of the CCAC.[326] Black carbon is not a well-mixed greenhouse gas, but a powerful climate-warming aerosol that is a component of fine particulate matter (specifically $PM_{2.5}$) that enters the atmosphere through the incomplete combustion of fossil fuels, including biofuels and biomass.[327] Fossil fuel combustion is the largest source of air pollution particles and tropospheric ozone, which kills 8–10 million [328] people every year. Cutting black carbon and tropospheric ozone can save up to 2.4 million lives every year and prevent the loss of crops by more than 50 million tons, worth US$ 4–33 billion a year, as calculated in 2011.[329]

Mitigation

- According to the CCAC, it is possible to reduce 70% of global black carbon emissions by 2030,[330] including by implementing the following measures:
    - Ensuring fast ratification of the Gothenburg Protocol and the 2012 amendment that includes controls for black carbon;[331]
    - Reducing on-road and off-road diesel emissions by mandating diesel particulate filters while eliminating diesel and other high-emitting vehicles and shifting to clean forms of transportation;[332]
    - Eliminating flaring, while shifting to clean energy;[333]
    - Switching to clean cooking and heating methods;[334] and
    - Banning heavy fuel oil in the Arctic and establishing black carbon emission standards for vessels by amending Annex VI of the International Convention for the Prevention of Pollution from Ships (MARPOL).[335]

D. Hydrofluorocarbons (HFCs)

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

Mitigation

- The Montreal Protocol on Substances that Deplete the Ozone Layer (Montreal Protocol) is successfully phasing out the production and use of ozone-depleting and potent climate pollutants, including chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), preventing GHG emissions that otherwise could have equaled or exceeded the emissions of CO_2 in 2010.[336] Avoided warming from the Montreal Protocol is delaying the first appearance of ice-free Arctic summer by up to 15 years.[337]

  - By end of the century, the Montreal Protocol's steady progress over its 35 years of operation will avoid up to 2.5 °C of warming by end of century that otherwise would have already pushed the planet past irreversible tipping points.[338] About 1.7 °C of this avoided warming comes from the Protocol's mandatory reduction of super polluting chemicals—CFCs, HCFCs, and now HFCs—used primarily as refrigerants in cooling equipment. An additional 0.85 °C of warming will be avoided by protecting our planet's forests and other carbon "sinks" from damaging ultraviolet radiation that reduce their ability to pull CO_2 out of the atmosphere and store it safely in terrestrial sinks.
  - This planet-saving climate benefit is in addition to achieving its original objective of putting the stratospheric ozone layer on the road to full recovery by 2066.[339]
  - Emissions of these ozone-depleting super climate pollutants between 1955 and 2005, were 20% more effective at warming than CO_2,[340] accounted for 37% of anthropogenic Arctic warming, and a third of the loss in September sea ice extent due to anthropogenic emissions.[341]
  - Narrowing exemptions for CFCs and HCFCs used as feedstocks (in plastics, for example) and produced as by-products could further ensure these benefits.[342] Atmospheric measurements reveal increasing concentrations of five CFCs banned under the Montreal Protocol but likely emitted as by-products and not subject to current controls.[343]
- 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.[344]
  - The initial phasedown schedule of the Kigali Amendment would lock in reductions limiting warming from HFCs in 2100 to about 0.04 °C, avoiding nearly 90% of the potential warming, or up to 0.44 °C.[345]
  - Efficient implementation of the Kigali Amendment could avoid nearly 0.1 °C of warming by 2050.[346]
  - Accelerating the phasedown could reduce HFC emissions by an additional 72% in 2050, increasing the chances of staying below 1.5 °C this century.[347]
  - In addition to a faster phasedown schedule, more mitigation is available from recycling and destroying HFC "banks" embedded in products and equipment; early replacement of older inefficient cooling equipment using the old HFC refrigerants; and reducing refrigerant leaks through better design, manufacturing, and servicing.[348]
  - Globally, adopting lifecycle refrigerant management practices, including reducing leaks and stopping end-of-life venting of HFCs from refrigerators and air conditioners, could avoid up to 91 $GtCO_2e$ of emissions by the end of the century.[349]
  - The Kigali Amendment also requires Parties to destroy HFC-23, a by-product of the production of HCFC-22, to the extent practicable, which will provide additional mitigation not included in the 0.5 °C calculation.[350]

  - Improving energy efficiency of cooling equipment during the HFC phasedown can more than double the climate benefits in CO_2e by reducing emissions from the fossil fuel power plants that are still providing the electricity to run the equipment.[351]
  - As of June 2023, 150 countries have accepted, ratified, or approved the Kigali Amendment, including China and India.[352]
  - The U.S. is implementing the Kigali phasedown schedule through the 2020 American Innovation and Manufacturing (AIM) Act. The AIM Act and related implementing regulations will reduce the production and consumption of HFCs by 85% by 2036.[353] Twelve U.S. states have instituted HFC prohibitions for products and equipment where low-GWP alternatives are available, and six more have proposed HFC bans.[354] On 21 September 2022, the U.S. Senate approved ratification of the Kigali Amendment.[355]

E. Nitrous oxide (N_2O)

While not short-lived and thus not an SLCP, N_2O is a potent GHG with a global warming potential over 100 years (GWP_{100}) that is 273 times greater than CO_2,[356] contributing the equivalent of about 10% of today's CO_2 warming.[357] It also is the most significant anthropogenic ozone-depleting substance (ODS) not yet controlled by the Montreal Protocol.[358] The Montreal Protocol's 2022 Quadrennial Assessment Report calculated that N_2O emissions accelerated over the last 20 years and now exceed the highest projections.[359] The anthropogenic N_2O emissions in 2020 were more than 20% of the ozone depleting potential of peak CFC emissions in 1987.[360]

Mitigation

- Controlling N_2O emissions could provide climate mitigation of about 1.67 $GtCO_2e$ GWP_{100} by 2050 with 0.94 $GtCO_2e$ from agriculture and about 0.6 $GtCO_2e$ from industry in 2050.[361]
- Under current policies, N_2O emissions are projected to rise by 8% from 2021–2030.
- Reducing N_2O emissions to levels compliant with the 1.5 °C Paris Agreement guardrail will have the added benefit of increasing stratospheric ozone at levels.
  - Such reductions will also reduce radiative forcing by 0.04 W m^{-2} averaged over 2023–2100,[362] more than half the decrease in radiative forcing resulting from eliminating HFCs.[363]
  - Full recovery of the ozone layer will be delayed if N_2O emissions continue to increase.[364]
- The agriculture, forestry, and land use sector (AFOLU) accounted for 82% of global anthropogenic N_2O emissions,[365] contributing approximately 1.8 $GtCO_2e$/yr between 2010 and 2019.[366]
- In the agriculture sector, several solutions are cost-effective in reducing N_2O emissions from agricultural processes, including precision farming using variable rate technology and nitrogen inhibitors that suppress the microbial activity that produces N_2O. Studies have found that variable rate technology can increase yields by 1–10% while reducing 4–37% of nitrogen fertilization.[367]
  - Adapting solutions for smallholder farmers in the Global South requires additional attention.[368]

    - Another potential solution, the SOP LAGOON product line,[369] stimulates nitrogen uptake in crops and inhibits GHG emissions from manure, according to peer-reviewed field experiments with the product.[370]
- For industry, most emissions are produced in the manufacture of nitric and adipic acids for a variety of uses. Proven abatement technology at nitric and adipic acid production facilities could reduce 86% of projected industrial N_2O emissions by 2030.[371]
    - In the industrial sector, abatement technology has been available and utilized by manufacturers in developed countries since the 1990s.[372] Moreover, only a few countries produce 86% of industrial N_2O: China, the United States, Egypt, and Russia.[373]
    - Out of the 39 adipic acid plants, one plant is in the U.S. and 11 plants in China operate without or with significantly lower pollution control technology than the industry standard abatement levels of 98%.[374]

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

A. Protecting Arctic albedo and permafrost

Rapid reductions in super climate pollutants are key to protecting the Arctic. The *Global Methane Assessment* calculated that strategies to cut methane emissions by 40–45% by 2030 could avoid nearly 0.3 °C by the 2040s, and 0.5 °C in the Arctic by 2050, 60% more than the global average.[375] The 2011 UNEP/WMO Integrated Assessment of Black Carbon and Tropospheric Ozone calculated that fully implementing measures targeting methane and black carbon could reduce the rate of global warming by half and reduce Arctic warming by two-thirds.[376]

- The Arctic is nearly five times more sensitive to black carbon emitted in the Arctic region than from similar emissions in the mid-latitudes.[377] In the Arctic, black carbon not only warms the atmosphere but also facilitates additional warming by darkening the snow and ice and reducing albedo, or reflectivity, allowing the darker surface to absorb extra solar radiation and cause further melting.[378]
    - Heavy-Fuel Oil (HFO) used in shipping is a significant source of black carbon and sulfates.[379] The International Maritime Organization (IMO) will ban HFO use in the Arctic beginning in July 2024 for some ships, with waivers and exemptions for others until July 2029.[380] (HFO has been banned in the Antarctic since 2011.[381])
    - Because of the exemptions, the HFO ban will not have a big impact this decade. If the measures that will go into effect in July 2024 had been in effect in 2019, they would have banned only 16% of HFO used in the Arctic and reduced only 5% of the black carbon.[382] However, if the Arctic HFO ban were imposed without the waivers or exemptions, black carbon emissions could have been reduced by 30%.[383]
    - In 2019, Arctic Council countries set a collective voluntary target of reducing black carbon emissions by 25–33% by 2025 compared to 2013 levels.[384] Adopting best available techniques could halve black carbon emissions by 2025 and surpass the current goal.[385] These reductions would improve air quality by reducing exposure of fine particle concentrations from 18 million to 1 million people by 2050 and avoid 40% of air pollution-related deaths in Arctic Council countries by mid-century.[386]

    - In 2021, the IMO adopted a voluntary resolution to reduce black carbon emissions in the Arctic after the annual meeting of the IMO's Marine Environment Protection Committee. In addition to this resolution, the Committee also agreed to revise their GHG Strategy, adopt a voluntary resolution on using cleaner fuel in the Arctic, and address marine plastic litter from ships.[387]
    - Banning investments in oil and gas development in the Arctic can help to further protect the region. All the major U.S. banks—Bank of America, Goldman Sachs, JP Morgan Chase, Wells Fargo, Citi, and Morgan Stanley—have committed not to fund oil and gas exploration in the Arctic.[388] Insurance companies are also starting to commit to banning coverage of Arctic oil projects, including AXA, Swiss RE, and Zurich Insurance.[389]
- Additional strategies being investigated for protecting and restoring Arctic ice include enhancing albedo of Arctic sea ice and thickening sea ice.[390]
    - Ocean Visions is currently developing an interactive roadmap on Arctic sea ice preservation tools and strategies that can help identify priorities for additional research, development, and potential testing.[391]

B. Protecting forests and other carbon sinks

About half of the anthropogenic CO_2 emitted each year is removed by the ocean and land sinks over the span of 30 years.[392] These sinks are slowing their carbon uptake, and some are approaching vulnerable tipping points. Carbon budget estimates do not account for catastrophic carbon sink loss, and thus the committed warming following net-zero will depend on the state of these carbon sinks.[393]

i. Land sinks at risk of tipping

Deforestation combined with global warming risks enhancing warming feedbacks and crossing ecosystem tipping points, including loss of the Amazon and boreal forest.[394] Halting the destruction of forests and other carbon sinks so they continue to store carbon and do not turn into sources of CO_2 can provide fast mitigation, while also protecting biodiversity.[395] This also requires stopping forest bioenergy, which is not a climate solution.[396]

- Under current warming trends, the global land sink, which now mitigates ~30% of carbon emissions and has avoided 0.4 °C since 1900,[397] could be cut by half as early as 2040, as increasing temperatures reduce photosynthesis and speed up respiration,[398] calling into question national pledges under the Paris Agreement that rely on land uptake of carbon to meet mitigation goals.[399] Loss of forests and other sinks contributes to warming through loss of carbon sinks and increased carbon dioxide and other GHG emissions (biogeochemical effect) through changes in the local surface energy budget (biophysical effect).
    - Tropical and boreal forest dieback could contribute up to 200 PgC [733 $GtCO_2$] by 2100.[400] If all of the carbon stored in the Amazon were released (10 years' worth of human emissions), the planet could warm by 0.3 °C.[401] The boreal forest carbon sink rivals the Amazon's, representing 30% of global forest area, and close to half of the global terrestrial carbon sink.[402]

    - Degradation of tropical moist forests contributes warming that may push these forests towards their tipping points. Patches of degraded tropical moist forests are on average 0.78 °C warmer than intact forests. CO_2 emissions from tropical forest degradation also contribute an average 0.026 °C across all tropical land areas (biogeochemical effect), which is comparable to the biophysical warming of 0.022 °C. The warming impacts from forest degradation could be extensive, as nearly a quarter (24%) of the world's tropical moist forests are degraded according to 2010 satellite images.[403] A ~4 °C increase in air temperatures could induce a tipping point that threatens the canopy of tropical forests by pushing vegetation past their upper temperature limit for photosynthesis.[404]
    - Accelerated warming in the boreal zones has intensified wildfires[405] and pest-outbreaks,[406] leading to large-scale tree mortality. Such events have been both abrupt and irreversible, as intermediate stages of boreal forest regeneration are proving unstable.[407] More frequent and severe fires increases the risk of boreal forests switching from a carbon sink to a carbon source,[408] and this switch has already occurred in North America due to boreal wildfires between 1985–2016.[409]
    - The increased incidence of boreal wildfires has been linked to drier air, or vapor pressure deficit (VPD), that draws moisture out of the soil and vegetation.[410] Soil desiccation is a self-amplifying feedback contributing additional warming,[411] which is projected to accelerate by mid-century under a high emissions scenario (SSP5-8.5), although it is significantly reduced under a low emissions scenario (SSP1-2.6).[412] If warming continues along a high-emissions trajectory, this feedback will amplify as early as mid-century and lead to an increase in fires across North America and Europe.[413] Nearly half of the increase in VPD is attributable to emissions from the world's top 88 carbon-emitting corporations.[414]
    - Warming is also shifting the range of boreal forests further north into bare snow-covered tundra, reducing albedo and creating warmer winters in the region.[415] While boreal forest range shifts have high potential to propel self-amplifying feedbacks, the net warming impact remains uncertain.[416]
- The Amazon forest is already within the bounds of its estimated tipping point, 20–40% of complete loss,[417] with 20% destroyed completely and an additional 6% beyond repair absent human intervention.[418]
    - Continued deforestation and drying in the Amazon under high-emissions scenarios could result in up to a 50% loss in forest cover by 2050.[419]
    - Changes to the global water cycle may be pushing the Amazon to a tipping point.[420] The combination of drier conditions, deforestation, and warming have been reducing Amazon forest resilience since 2000, increasing the risk of dieback.[421]
    - With increased deforestation, including from fires, greater disturbances, and higher temperatures, there is a point beyond which the Amazon rainforest would be difficult to reestablish,[422] with recent measurements suggesting that the southeastern area of the Amazon has already shifted to a net carbon source as tree mortality increases and photosynthesis decreases.[423]
- Conservation International estimates that Earth's ecosystems contain 139 billion metric tons (Gt C) [510 $GtCO_2$] of "irrecoverable carbon," defined as carbon stored in natural systems that "are vulnerable to release from human activity and, if lost, could not be restored by 2050." The highest concentrations of irrecoverable carbon are in the Amazon

(31.5 Gt C) [115.5 $GtCO_2$], the Congo Basin (8.1 Gt C) [29.7 $GtCO_2$], and New Guinea (7.3 Gt C) [26.8 $GtCO_2$], with additional reserves in boreal forests, mangroves, and peatlands.[424]

Nature-based solutions help limit warming in three ways: first, protecting forests and sinks prevents the release of carbon; second, restoring critical forests and sinks sequester carbon; and third, improving land management can both reduce emissions of carbon, methane, and N_2O and sequester carbon.[425]

- Effective ways to protect forests, peatlands, and other sinks include:
    - Promoting forest protection and proforestation to allow existing forests to achieve their full ecological potential;[426]
    - Preserving existing peatlands and restoring degraded peatlands;[427]
    - Restoring coastal "blue carbon" ecosystems;[428] and
    - Prohibiting bioenergy.[429]
- Global government-led efforts to protect forests are increasing.
    - At COP26, world leaders agreed to halt deforestation by 2030 in the Glasgow Leaders' Declaration on Forests and Land Use. As of February 2023, 145 countries have committed to this agreement, including Brazil, China, Russia, and the United States, covering about 91% of the world's forests.[430] This declaration includes US$ 12 billion in funding for forest-related climate finance between 2021–2025, an additional US$ 7 billion in funding from private companies, and a global roadmap to make 75% of forest commodity supply chains sustainable.[431]
    - The U.S. launched a parallel domestic Plan to Conserve Global Forests: Critical Carbon Sinks. This is an "all-of-government effort" to end natural forest loss, preserve global ecosystems, including carbon sinks, and restore at least an additional 200 million hectares of forests and other ecosystems by 2030, with a dedicated fund of US$ 9 billion to support this effort.[432]

ii. The ocean carbon sink is weakening

The ocean carbon sink, which has absorbed roughly 30% of anthropogenic CO_2 emissions since the industrial revolution,[433] is weakening, with carbon uptake slowing by 15% between 1994-2014.[434] Half of this recent slow-down is from anticipated declines in the ocean's capacity to absorb CO_2 due to rising atmospheric CO_2 and warmer ocean temperatures. The rest of this recent slow-down is attributable to warming-induced declines in ocean mixing, especially weakening of the AMOC, which normally transports CO_2-rich waters to the deep ocean.[435] If slowing ocean uptake continues, more aggressive emissions reductions will be required to meet net-zero targets, as they assume a static ocean carbon sink.[436]

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

Even though CH_4 is short-lived in the atmosphere, lasting only about 10 years, there are significant benefits to removing CH_4 before it can realize its full impact on the climate system. Short-lived does not mean short-term impacts; temperature anomalies from methane emissions can persist for centuries. This is due to carbon-climate feedbacks and inertia in the climate system, including in ocean heat.[437] The U.S. National Academies of Sciences, Engineering, and Medicine is developing a research agenda on atmospheric methane removal,[438] following pioneering work by Professor Rob Jackson at Stanford. Pathways under consideration to remove methane from the atmosphere include catalytic oxidation, microbial filters, and augmentation of natural sinks.[439] Catalytic systems are likely to involve technology already being developed for application to environments with heightened methane concentrations, such as coal mines and dairy barns. Additionally, other climate interventions have started looking further into monitoring methane and other GHG emissions to determine the best roadmap for research.[440]

- The U.S. government is exploring options to remove methane from the atmosphere.
    - In April 2021, the Department of Energy's Advanced Research Projects Agency-Energy (ARPA-E) announced a US$ 35 million program to reduce methane emissions, called REMEDY (Reducing Emissions of Methane Every Day of the Year). This three-year research program looks to reduce methane emissions from the oil, gas, and coal sectors. According to ARPA-E, these three sources contribute to at least 10% of U.S. anthropogenic methane emissions.[441] In developing the REMEDY program, ARPA-E recognized the need for further research on methane capture from the air in parallel with efforts to capture CO_2.[442]
    - In December 2021, ARPA-E awarded grants for a catalytic oxidation system targeting lean-burn natural-gas-fired engine exhaust, multiple catalysis-based systems for coal-mine ventilation, and the development of a low-cost, copper-based catalyst.[443]
- Other methane removal interventions might target natural methane sources.
    - One company is testing the possibility of installing passive systems to capture and flare methane bubbling from Arctic lakes.[444]
    - Other pathways, such as the augmentation of natural sinks could also develop into viable strategies.[445] Observations of Sahara dust suggest a mechanism for increasing active chlorine with potential to enhance the methane sink.[446] However, a recent modeling study found that chlorine levels in the atmosphere would need to be more than tripled to reduce methane levels, and smaller chlorine increases could increase methane levels.[447]
- These methane and non-CO_2 removal efforts could complement carbon removal projects in the U.S.,[448] Europe,[449] and elsewhere.[450]

6. Conclusion

Global warming is projected to cross the 1.5 °C guardrail as soon as the early 2030s. Policies that rely on decarbonization alone are insufficient to slow the near-term warming to keep the planet below 1.5 °C or even below the more dangerous 2.0 °C threshold.

We need to urgently broaden our approach to climate mitigation to target both CO_2 and other largely neglected super climate pollutants to address the near-term and long-term impacts of climate disruption, avoid or at least delay irreversible tipping points, and maintain a livable planet.[451]

Combining efforts to cut CO_2 emissions by decarbonizing the energy system *with* mitigation measures targeting non-CO_2 super climate pollutants methane, HFC refrigerants, black carbon soot, and ground-level ozone smog, as well as nitrous oxide, would reduce the rate of warming by half from 2030 to 2050, which would slow the rate of warming a decade or two earlier than decarbonization alone, *making it possible for the world to stay below the 1.5 ℃ guardrail*[452] *and avoid triggering a cascade of tipping points*.[453] This strategy of a sprint this decade to slow warming in the near term by cutting super climate pollutants and protecting carbon sinks through nature-based solutions complements the marathon to net zero CO_2 emissions by 2050 to stabilize temperatures in the longer term.[454]

As UN Secretary-General António Guterres said, AR6 is a "code red" for the climate emergency.[455] The IPCC's 2018 *Special Report on 1.5 °C* presented the three essential strategies for keeping the planet relatively safe: reducing CO_2, reducing super climate pollutants, and removing up to 1 trillion tons of CO_2 from the atmosphere by 2100.[456] Cutting super climate pollutants is the only known strategy that can slow warming and feedbacks in time to avoid catastrophic and perhaps existential impacts[457] from Hothouse Earth,[458] other than perhaps solar radiation management, which carries its own risks and governance challenges.[459]

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

> "Four shifts in focus reflect this new architecture; first, the near-unanimous recognition of the impending climate emergency and the need to limit warming to 1.5 degrees Celsius; second, the recognition "that 2030 is the new 2050," as French President Emmanuel Macron said, and that major emission cuts have to be made in this decade (note also that the U.S.-China Joint Glasgow Declaration marked the first time that the United States and China acknowledged the urgency of climate action in this "critical decade" of the 2020s); third, the recognition that cutting non-CO_2 emissions (particularly methane) is essential for slowing warming in the next couple of decades and that cuts to CO_2 alone cannot address the near-term emergency; and fourth, the addition of sector-specific approaches in recognition that it is often more efficient and effective to address individual sectors of the economy in reaching climate solutions."[460]

References

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[1] Dreyfus G. B., Xu Y., Shindell D. T., Zaelke D., & Ramanathan V. (2022) *Mitigating climate disruption in time: A self-consistent approach for avoiding both near-term and long-term global warming*, Proc. Nat'l. Acad. Sci. 119(22): 1–8, 1, 5 ("We find that mitigation measures that target only decarbonization are essential for strong long-term cooling but can result in weak near-term warming (due to unmasking the cooling effect of co-emitted aerosols) and lead to temperatures exceeding 2°C before 2050. In contrast, pairing decarbonization with additional mitigation measures targeting short-lived climate pollutants (SLCPs) and N_2O, slows the rate of warming a decade or two earlier than decarbonization alone and avoids the 2°C threshold altogether. These non-CO_2 targeted measures when combined with decarbonization can provide net cooling by 2030, reduce the rate of warming from 2030 to 2050 by about 50%, roughly half of which comes from methane, significantly larger than decarbonization alone over this timeframe. … Aggressive decarbonization to achieve net-zero CO_2 emissions in the 2050s (as in the decarb-only scenario) results in weakly accelerated net warming compared to the reference case, with a positive warming up to 0.03 °C in the mid-2030s, and no net avoided warming until the mid-2040s due to the reduction in co-emitted cooling aerosols (Figure 3a). By 2050, decarbonization measures result in very limited net avoided warming (0.07°C), consistent with Shindell and Smith, but rise to a likely detectable 0.25°C by 2060 and a major benefit of 1.4°C by 2100 (Table S5). In contrast, pairing decarbonization with mitigation measures targeting CH_4, BC, HFC, and N_2O (not an SLCP due to its longer lifetime) independent from decarbonization are essential to slowing the rate of warming by the 2030s to under 0.3°C per decade (Table 1, Figure 3b), similar to the 0.2°C to 0.25°C per decade warming prior to 2020. Recent studies suggest that rate of warming rather than level of warming controls likelihood of record-shattering extreme weather events. By 2050, the net avoided warming from the targeted non-CO_2 measures is 0.26°C, almost 4 times larger than the net benefit of decarbonization alone (0.07°C) (Table S5)."). *See also* Xu Y. & Ramanathan V. (2017) *Well below 2 °C: Mitigation strategies for avoiding dangerous to catastrophic climate changes*, Proc. Nat'l. Acad. Sci. 114(39): 10315–10323, 10321 ("Constrained by CO_2 lifetime and the diffusion time of new technologies (decades), the scenarios considered here (SI Appendix, Fig. S2A) suggest that about half of the 2.6 °C CO_2 warming in the baseline-fast scenario can be mitigated by 2100 and only 0.1–0.3 °C can be mitigated by 2050… The SP [super pollutant] lever targets SLCPs. Reducing SLCP emissions thins the SP blanket within few decades, given the shorter lifetimes of SLCPs (weeks for BC to about 15 years for HFCs). The mitigation potential of the SP lever with a maximum deployment of current technologies … is about 0.6 °C by 2050 and 1.2 °C by 2100 (SI Appendix, Fig. S5B and Table S1).").

[2] United Nations Environment Programme & World Meteorological Organization (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone, 254, 262 ("Evaluating global mean temperature change, it was found that the targeted measures to reduce emissions of methane and BC could greatly reduce warming rates over the next few decades (Figure 6.1; Box 6.1). When all measures are fully implemented, warming during the 2030s relative to the present would be only half as much as in the reference scenario. In contrast, even a fairly aggressive strategy to reduce CO_2 emissions, as for the CO_2-measures scenario, does little to mitigate warming until after the next 20-30 years (Box 6.2) … Large impacts of the measures examined here were also seen for the Arctic despite the minimal amount of emissions currently taking place there. This occurs due to the high sensitivity of the Arctic both to pollutants that are transported there from remote sources and to radiative forcing that takes place in areas of the northern hemisphere outside the Arctic. The 16 measures examined here, including the measures on pellet stoves and coal briquettes, reduce warming in the Arctic by 0.7 ºC (range 0.2 to 1.3 ºC) at 2040. This is a large portion of the 1.1 ºC (range 0.7 to 1.7 ºC) warming projected under the reference scenario for the Arctic, and hence implementation of the measures would be virtually certain to substantially slow, but not halt, the pace of Arctic climate change."). *See also* Shindell D., *et al.* (2012) *Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security*, Science 335(6065): 183–189, 184–185 ("The global mean response to the CH_4 plus BC measures was –0.54 ± 0.05ºC in the climate model. … Roughly half the forcing is relatively evenly distributed (from the CH_4 measures). The other half is highly inhomogeneous, especially the strong BC forcing, which is greatest over bright desert and snow or ice surfaces. Those areas often exhibit the largest warming mitigation, making the regional temperature response to aerosols and ozone quite distinct from the more homogeneous response to well-mixed greenhouse gases…. BC albedo and direct forcings are large in the Himalayas, where there is an especially pronounced response in the Karakoram, and in the Arctic, where the measures reduce projected warming over the next three decades by approximately two thirds and where regional temperature response patterns correspond fairly closely to

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albedo forcing (for example, they are larger over the Canadian archipelago than the interior and larger over Russia than Scandinavia or the North Atlantic).”); *and* Szopa S., Naik V., Adhikary B., Artaxo P., Berntsen T., Collins W. D., Fuzzi S., Gallardo L., Kiendler-Scharr A., Klimont Z., Liao H., Unger N., & Zanis P. (2021) *Chapter 6: Short-lived climate forcers*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 821 (“Across the SSPs, the collective reduction of CH_4, ozone precursors and HFCs can make a difference of global mean surface air temperature of 0.2 with a very likely range of [0.1–0.4] °C in 2040 and 0.8 with a very likely range of [0.5–1.3] °C at the end of the 21st century (comparing SSP3-7.0 and SSP1-1.9), which is substantial in the context of the Paris Agreement. Sustained methane mitigation, wherever it occurs, stands out as an option that combines near- and long-term gains on surface temperature (*high confidence*) and leads to air quality benefits by reducing surface ozone levels globally *(high confidence*).”).

[3] Ramanathan V. & von Braun J. (Eds.) (2023) *Resilience of People and Ecosystems under Climate Stress*, Proceedings of a Conference, Casina Pio IV, Vatican City, 13-14 July 2022, Libreria Editrice Vaticana: Vatican City, 20 (“Climate resilience needs to be built on three pillars: First Pillar – Mitigation to reduce climate change risks; Second Pillar – Adaptation to reduce exposure and vulnerability to climate changes that are unavoidable; and Third Pillar – Transformation of society to develop the capacity to prepare and plan for mitigation and adaptation. This transformation needs to happen bottom-up from the level of an individual and a community to national level.”). *See also* von Braun J., Ramanathan V., & Turkson P. K. A. (2022) *Resilience of people and ecosystems under climate stress*, Pontifical Academy of Sciences, 6 (“Recommendations: *Resilience building must rest on three pillars*: Mitigation, Adaptation & Transformation. Mitigation: *Reduce climate risks*…. Adaptation: *Reduce exposure and vulnerability to unavoidable climate risks.* Exposure & vulnerability reduction has three faces: Reductions in sensitivity to climate change; Reductions in risk exposure; & enhancement of adaptative capacity. There are limits to adaptation and hence adaptation has to be integrated with mitigation actions to avoid crossing the limits.”); where the definition of resilience is taken from Möller V., van Diemen R., Matthews J. B. R., Méndez C., Semenov S., Fuglestvedt J. S., & Resinger A. (2022) *Annex II: Glossary*, *in* Climate Change 2022: Impacts, Adaptation, and Vulnerability, *Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Pörtner H.-O., Roberts D. C., Tignor M., Poloczanska E. S., Mintenbeck K., Alegría A., Craig M., Langsdorf S., Löschke S., Möller V., Okem A., & Rama B. (eds.), 2920–2921 (“The capacity of interconnected social, economic and ecological systems to cope with a hazardous event, trend or disturbance, responding or reorganising in ways that maintain their essential function, identity and structure. Resilience is a positive attribute when it maintains capacity for adaptation, learning and/or transformation (Arctic Council, 2016).”).

[4] Intergovernmental Panel on Climate Change (2023) AR6 Synthesis Report: Climate Change 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 36 (“At 2°C of global warming, overall risk levels associated with the unequal distribution of impacts (RFC3), global aggregate impacts (RFC4) and large-scale singular events (RFC5) would be transitioning to high (*medium confidence*), those associated with extreme weather events (RFC2) would be transitioning to very high (*medium confidence*), and those associated with unique and threatened systems (RFC1) would be very high (*high confidence*) (Figure 3.3, panel a). With about 2°C warming, climate-related changes in food availability and diet quality are estimated to increase nutrition-related diseases and the number of undernourished people, affecting tens (under low vulnerability and low warming) to hundreds of millions of people (under high vulnerability and high warming), particularly among low-income households in low- and middle-income countries in sub-Saharan Africa, South Asia and Central America (*high confidence*). For example, snowmelt water availability for irrigation is projected to decline in some snowmelt dependent river basins by up to 20% (*medium confidence*). Climate change risks to cities, settlements and key infrastructure will rise sharply in the mid- and long-term with further global warming, especially in places already exposed to high temperatures, along coastlines, or with high vulnerabilities (*high confidence*).”).

[5] Fischer E. M., Sippel S., & Knutti R. (2021) *Increasing probability of record-shattering climate extremes*, Nat. Clim. Change 11: 689–685, Supplementary Information (“In the main manuscript, we illustrate a fundamental difference in the behavior of (i) the statistically expected return levels or return periods of extremes traditionally

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defined as anomalies relative to a reference period, i.e. the probability of exceeding a fixed threshold and (ii) the expected probability of record-shattering extremes. For (i) the statistically expected return periods and levels are largely proportional to the warming level independent of the emission pathway (RCP/SSP), whereas for (ii) the statistically expected probability differs for the same warming level depending on the warming rate of the underlying forced response (i.e. the multi-member mean warming) and thereby on the emission pathway (RCP or SSP).").

[6] Xu Y., Ramanathan V., & Victor D. G. (2018) *Global warming will happen faster than we think*, Nature 564(7734): 30–32, 31 ("In 2017, industrial carbon dioxide emissions are estimated to have reached about 37 gigatonnes[2]. This puts them on track with the highest emissions trajectory the IPCC has modelled so far. This dark news means that the next 25 years are poised to warm at a rate of 0.25–0.32 °C per decade[3]. That is faster than the 0.2 °C per decade that we have experienced since the 2000s, and which the IPCC used in its special report."). *See also* Hansen J. E., Sato M., Simons L., Nazarenko L. S., Sangha I., von Schuckmann K., Loeb N. G., Osman M. B., Jin Q., Kharecha P., Tselioudis G., Jeong E., Lacis A., Ruedy R., Russell G., Cao J., & Li J. (23 May 2023) *Global warming in the pipeline*, IZV. Atmos. Ocean. Phys. (*preprint*): 1–62, 39 ("With current policies, we expect climate forcing for a few decades post-2010 to increase 0.5-0.6 W/m^2 per decade and produce global warming at a rate of at least +0.27°C per decade. In that case, global warming should reach 1.5°C by the end of the 2020s and 2°C by 2050 (Fig. 25)." … Figure 25 caption reads "Edges of the predicted post-2010 accelerated warming rate (see text) are 0.36 and 0.27°C per decade.").

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

[8] *See* Copernicus Climate Services (9 January 2023) *2022 was a year of climate extremes, with record high temperatures and rising concentrations of greenhouse gases* ("2022 was the 5th warmest year – however, the 4th-8th warmest years are very close together. The last eight years have been the eight warmest on record. The annual average temperature was 0.3°C above the reference period of 1991-2020, which equates to approximately 1.2°C higher than the period 1850-1900. Atmospheric carbon dioxide concentrations increased by approximately 2.1 ppm, similar to the

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rates of recent years. Methane concentrations in the atmosphere increased by close to 12 ppb, higher than average, but below the last two years' record highs. La Niña conditions persisted during much of the year, for the third year in a row"); National Aeronautics and Space Administration (12 January 2023) *NASA Says 2022 Fifth Warmest Year on Record, Warming Trend Continues*; *and* National Oceanic and Atmospheric Administration (12 January 2022) *2022 was world's 6th-warmest year on record*. *See also* World Meteorological Organization (10 July 2023) *Preliminary data shows hottest week on record. Unprecedented sea surface temperatures and Antarctic sea ice loss* ("The exceptional warmth in June and at the start of July occurred at the onset of the development of El Niño, which is expected to further fuel the heat both on land and in the oceans and lead to more extreme temperatures and marine heatwaves," said Prof. Christopher Hewitt, WMO Director of Climate Services.").

[9] Copernicus Climate Change Service (6 July 2023) *Record-breaking North Atlantic Ocean temperatures contribute to extreme marine heatwaves* ("So far this year, discussions of our oceans and climate have largely focused on the onset of El Niño, recently declared by the World Meteorological Organization, and its potential for pushing global temperatures into "uncharted territory" by the end of 2023 and into 2024. But in fact, we have already entered uncharted territory due to the exceptionally warm conditions in the north Atlantic Ocean.").

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

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

[12] Hansen J., Sato M., & Ruedy R. (12 January 2023) *Global Temperature in 2022*, Columbia University, 1 ("Global surface temperature in 2022 was +1.16°C (2.1°F) in the GISS (Goddard Institute for Space Studies) analysis[1,2,3]

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

[13] Intergovernmental Panel on Climate Change (2023) AR6 Synthesis Report: Climate Change 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 6 (footnote 8: "For 1850–1900 to 2013–2022 the updated calculations are 1.15°C [1.00°C–1.25°C] for global surface temperature, 1.65°C [1.36°C– 1.90°C] for land temperatures and 0.93°C [0.73°C–1.04°C] for ocean temperatures above 1850–1900 using the exact same datasets (updated by 2 years) and methods as employed in WGI); 6 ("Observed warming is human-caused, with warming from greenhouse gases (GHG), dominated by CO_2 and methane (CH_4), partly masked by aerosol cooling (Figure 2.1).").

[14] Intergovernmental Panel on Climate Change (2021) *Summary for Policymakers*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), SPM-5 ("Each of the last four decades has been successively warmer than any decade that preceded it since 1850. Global surface temperature in the first two decades of the 21st century (2001-2020) was 0.99 [0.84-1.10] °C higher than 1850-1900[9]…. Global surface temperature was 1.09 [0.95 to 1.20] °C higher in 2011–2020 than 1850–1900, with larger increases over land (1.59 [1.34 to 1.83] °C) than over the ocean (0.88 [0.68 to 1.01] °C). The estimated increase in global surface temperature since AR5 is principally due to further warming since 2003–2012 (+0.19 [0.16 to 0.22] °C). Additionally, methodological advances and new datasets contributed approximately 0.1ºC to the updated estimate of warming in AR6[10]."… Footnote 10: "Since AR5, methodological advances and new datasets have provided a more complete spatial representation of changes in surface temperature, including in the Arctic. These and other improvements have additionally increased the estimate of global surface temperature change by approximately 0.1 ºC, but this increase does not represent additional physical warming since the AR5."). *See also* National Oceanic and Atmospheric Administration National Centers for Environmental Information (2022) *September 2022 Global Climate Report* ("The January–September global surface temperature was 0.86°C (1.55°F) above the 1901-2000 average of 14.1°C (57.5°F) — the sixth-highest January–September temperature in the 143-year record. The ten warmest January–September periods on record have occurred since 2010. According to NCEI's statistical analysis, the year 2022 is very likely to rank among the ten warmest years on record but a less than 5% chance to rank among the five warmest years on record.").

[15] Forster P. M., *et al.* (2023) *Indicators of Global Climate Change 2022: annual update of large-scale indicators of the state of the climate system and human influence*, Earth Syst. Sci. Data 15(6): 2295–2327, 2296 ("The indicators show that human-induced warming reached 1.14 [0.9 to 1.4] ◦C averaged over the 2013–2022 decade and 1.26 [1.0 to 1.6] ◦C in 2022. Over the 2013–2022 period, human-induced warming has been increasing at an unprecedented rate of over 0.2 ◦C per decade."). See also Intergovernmental Panel on Climate Change (2021) *Summary for Policymakers*, in Climate Change 2021: The Physical Science Basis, Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Masson-Delmotte V., *et al.* (eds.), SPM-5 ("The likely range of total human-caused global surface temperature increase from 1850–1900 to 2010–2019 [11] is 0.8°C to 1.3°C, with a best estimate of 1.07°C. It is likely that well-mixed GHGs contributed a warming of 1.0°C to 2.0°C, other human drivers (principally aerosols) contributed a cooling of 0.0°C to 0.8°C, natural drivers changed global surface temperature by –0.1°C to 0.1°C, and internal variability changed it by –0.2°C to 0.2°C. It is very likely that well-mixed GHGs were the main driver[12] of tropospheric warming since 1979, and extremely likely that human-caused

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stratospheric ozone depletion was the main driver of cooling of the lower stratosphere between 1979 and the mid-1990s." … Footnote 11: "The period distinction with A.1.2 arises because the attribution studies consider this slightly earlier period. The observed warming to 2010–2019 is 1.06 [0.88 to 1.21] °C." … Footnote 12: "Throughout this SPM, 'main driver' means responsible for more than 50% of the change.").

[16] Forster P. M., *et al.* (2023) *Indicators of Global Climate Change 2022: annual update of large-scale indicators of the state of the climate system and human influence*, Earth Syst. Sci. Data 15(6): 2295–2327, 2311 ("The attribution assessment in WGI AR6 concluded that, averaged for the 2010–2019 period, all observed warming was human-induced, with solar and volcanic drivers and internal climate variability estimated not to make a contribution. This conclusion remains the same for the 2013–2022 period. Generally, whatever methodology is used, the best estimate of the human-induced warming to date is (within small uncertainties) equal to the observed warming to date.").

[17] Forster P. M., *et al.* (2023) *Indicators of Global Climate Change 2022: annual update of large-scale indicators of the state of the climate system and human influence*, Earth Syst. Sci. Data 15(6): 2295–2327, 2296 ("The indicators show that human-induced warming reached 1.14 [0.9 to 1.4] ◦C averaged over the 2013–2022 decade and 1.26 [1.0 to 1.6] ◦C in 2022. Over the 2013–2022 period, human-induced warming has been increasing at an unprecedented rate of over 0.2 ◦C per decade.").

[18] *See* Arias P. A., *et al.* (2021) *Technical Summary*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 42 ("Timing of crossing 1.5°C global warming: Slightly different approaches are used in SR1.5 and in this Report. SR1.5 assessed a likely range of 2030 to 2052 for reaching a global warming level of 1.5°C (for a 30-year period), assuming a continued, constant rate of warming. In AR6, combining the larger estimate of global warming to date and the assessed climate response to all considered scenarios, the central estimate of crossing 1.5°C of global warming (for a 20-year period) occurs in the early 2030s, ten years earlier than the midpoint of the likely range assessed in the SR1.5, assuming no major volcanic eruption. (TS.1.3, Cross-Section Box TS.1)"); *and* Lee J.-Y., Marotzke J., Bala G., Cao L., Corti S., Dunne J. P., Engelbrecht F., Fischer E., Fyfe J. C., Jones C., Maycock A., Mutemi J., Ndiaye O., Panickal S., & T. Zhou (2021) *Chapter 4: Future Global Climate: Scenario-Based Projections and Near-Term Information*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 555 ("The threshold-crossing time is defined as the midpoint of the first 20-year period during which the average GSAT exceeds the threshold. In all scenarios assessed here except SSP5-8.5, the central estimate of crossing the 1.5°C threshold lies in the early 2030s. This is in the early part of the *likely* range (2030–2052) assessed in the IPCC Special Report on Global Warming of 1.5°C (SR1.5), which assumed continuation of the then-current warming rate; this rate has been confirmed in the AR6. Roughly half of this difference between assessed crossing times arises from a larger historical warming diagnosed in AR6. The other half arises because for central estimates of climate sensitivity, *most scenarios show stronger warming over the near term than was assessed as 'current' in SR1.5* (*medium confidence*)."). Emphasis added.

[19] Diffenbaugh N. S. & Barnes E. A. (2023) *Data-driven predictions of the time remaining until critical global warming thresholds are reached*, Proc. Nat'l. Acad. Sci. 120(6): 1–9, 2 ("For 1.5 °C, the observed pattern of annual temperature anomalies in 2021 leads to a predicted time-to-threshold of 2035 (2030 to 2040) in the High scenario, 2033 (2028 to 2039) in the Intermediate scenario, and 2033 (2026 to 2041) in the Low scenario (Fig. 3). For 2 °C, the observed pattern of annual temperature anomalies in 2021 leads to a predicted time-to-threshold of 2050 (2043 to 2058) in the High scenario, 2049 (2043 to 2055) in the Intermediate scenario, and 2054 (2044 to 2065) in the Low scenario."), *discussed in* Harvey C. (31 January 2023) *AI Predicts Warming Will Surpass 1.5 C in a Decade*, Scientific American. *See also* Xu Y., Ramanathan V., & Victor D. G. (2018) *Global warming will happen faster than we think*, Comment, Nature 564(7734): 30–32, 30–31 ("But the latest IPCC special report underplays another alarming fact: global warming is accelerating. Three trends—rising emissions, declining air pollution and natural climate cycles—will combine over the next 20 years to make climate change faster and more furious than anticipated. In our view, there's a good chance that we could breach the 1.5 °C level by 2030, not by 2040 as projected in the special report (see 'Accelerated warming'). The climate-modelling community has not grappled enough with the rapid changes that policymakers care most about, preferring to focus on longer-term trends and equilibria."). Since Xu,

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Ramanathan, and Victor comment was published, the IPCC has updated its estimate for when 1.5 °C will be exceeded: *see* Arias P. A., *et al.* (2021) *Technical Summary*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 42 ("Timing of crossing 1.5°C global warming: Slightly different approaches are used in SR1.5 and in this Report. SR1.5 assessed a likely range of 2030 to 2052 for reaching a global warming level of 1.5°C (for a 30-year period), assuming a continued, constant rate of warming. In AR6, combining the larger estimate of global warming to date and the assessed climate response to all considered scenarios, the central estimate of crossing 1.5°C of global warming (for a 20-year period) occurs in the early 2030s, ten years earlier than the midpoint of the likely range assessed in the SR1.5, assuming no major volcanic eruption. (TS.1.3, Cross-Section Box TS.1)"); *and* Lee J.-Y., Marotzke J., Bala G., Cao L., Corti S., Dunne J. P., Engelbrecht F., Fischer E., Fyfe J. C., Jones C., Maycock A., Mutemi J., Ndiaye O., Panickal S., & T. Zhou (2021) *Chapter 4: Future Global Climate: Scenario-Based Projections and Near-Term Information*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 555 ("The threshold-crossing time is defined as the midpoint of the first 20-year period during which the average GSAT exceeds the threshold. In all scenarios assessed here except SSP5-8.5, the central estimate of crossing the 1.5°C threshold lies in the early 2030s. This is in the early part of the *likely* range (2030–2052) assessed in the IPCC Special Report on Global Warming of 1.5°C (SR1.5), which assumed continuation of the then-current warming rate; this rate has been confirmed in the AR6. Roughly half of this difference between assessed crossing times arises from a larger historical warming diagnosed in AR6. The other half arises because for central estimates of climate sensitivity, most scenarios show stronger warming over the near term than was assessed as 'current' in SR1.5 (*medium confidence*)."). *See also* Dvorak M. T., Armour K. C., Frierson D. M. W., Proistosescu C., Baker M. B., & Smith C. J. (2022) *Estimating the timing of geophysical commitment to 1.5 and 2.0 °C of global warming*, NAT. CLIM. CHANGE 12: 547–552, 547 ("Following abrupt cessation of anthropogenic emissions, decreases in short-lived aerosols would lead to a warming peak within a decade, followed by slow cooling as GHG concentrations decline. This implies a geophysical commitment to temporarily crossing warming levels before reaching them. Here we use an emissions-based climate model (FaIR) to estimate temperature change following cessation of emissions in 2021 and in every year thereafter until 2080 following eight Shared Socioeconomic Pathways (SSPs). Assuming a medium-emissions trajectory (SSP2–4.5), we find that we are already committed to peak warming greater than 1.5 °C with 42% probability, increasing to 66% by 2029 (340 $GtCO_2$ relative to 2021). Probability of peak warming greater than 2.0 °C is currently 2%, increasing to 66% by 2057 (1,550 $GtCO_2$ relative to 2021). Because climate will cool from peak warming as GHG concentrations decline, committed warming of 1.5 °C in 2100 will not occur with at least 66% probability until 2055."); *and* Hansen J. E., Sato M., Simons L., Nazarenko L. S., Sangha I., von Schuckmann K., Loeb N. G., Osman M. B., Jin Q., Kharecha P., Tselioudis G., Jeong E., Lacis A., Ruedy R., Russell G., Cao J., & Li J. (23 May 2023) *Global warming in the pipeline*, IZV. ATMOS. OCEAN. PHYS. (*preprint*): 1–62, 39 ("With current policies, we expect climate forcing for a few decades post-2010 to increase 0.5-0.6 W/m^2 per decade and produce global warming at a rate of at least +0.27°C per decade. In that case, global warming should reach 1.5°C by the end of the 2020s and 2°C by 2050 (Fig. 25).").

[20] Trewin B. (2022) *Assessing Internal Variability of Global Mean Surface Temperature From Observational Data and Implications for Reaching Key Thresholds*, J. GEOPHYS. RES. ATMOS. 127(23): 1–9, 7 ("This indicates that, providing there is no major change in the underlying warming rate, the probability that 1.5°C has been crossed on or before the current year is substantially above 50% once the observed mean for the most recent 11 years reaches 1.43°C. The probability is about 90% once the 11-year mean reaches 1.44°C, while crossing is unlikely to have occurred if the observed 11-year mean is below 1.40°C.").

[21] Intergovernmental Panel on Climate Change (2023) AR6 SYNTHESIS REPORT: CLIMATE CHANGE 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 33 ("Modelled pathways consistent with the continuation of policies implemented by the end of 2020 lead to global warming of 3.2 [2.2-3.5]°C (5–95% range) by 2100 (*medium confidence*) (see also Section 2.3.1). Pathways of >4°C (≥50%) by 2100 would imply a reversal of current technology and/or mitigation policy trends (*medium confidence*). However, such warming could occur in

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emissions pathways consistent with policies implemented by the end of 2020 if climate sensitivity or carbon cycle feedbacks are higher than the best estimate (*high confidence*).").

[22] Hansen J. E., Sato M., Simons L., Nazarenko L. S., Sangha I., von Schuckmann K., Loeb N. G., Osman M. B., Jin Q., Kharecha P., Tselioudis G., Jeong E., Lacis A., Ruedy R., Russell G., Cao J., & Li J. (23 May 2023) *Global warming in the pipeline*, IZV. ATMOS. OCEAN. PHYS. (*preprint*): 1–62, 13 ("If ECS is 4°C (1°C per W/m^2), more warming is in the pipeline than widely assumed. GHG forcing today already exceeds 4 W/m^2. Aerosols reduce the net forcing to about 3 W/m^2, based on IPCC estimates (Section 5), but warming still in the pipeline for 3 W/m^2 forcing is 1.8°C, exceeding warming realized to date (1.2°C). Slow feedbacks increase the equilibrium response even further (Section 6). Large warmings can be avoided via a reasoned policy response, but definition of effective policies will be aided by an understanding of climate response times."). *See also* pages 1, 41 ("Equilibrium global warming including slow feedbacks for today's human-made greenhouse gas (GHG) climate forcing (4.1 W/m^2) is 10°C, reduced to 8°C by today's aerosols. Decline of aerosol emissions since 2010 should increase the 1970-2010 global warming rate of 0.18°C per decade to a post-2010 rate of at least 0.27°C per decade. Under the current geopolitical approach to GHG emissions, global warming will likely pierce the 1.5°C ceiling in the 2020s and 2°C before 2050. Impacts on people and nature will accelerate as global warming pumps up hydrologic extremes. … One merit of consistent analysis for the full Cenozoic era is revelation that the human-made climate forcing exceeds the forcing at transition from a largely ice-free planet to glaciated Antarctica, even with inclusion of a large, negative, aerosol climate forcing. Equilibrium global warming for today's GHG level is 10°C for our central estimate ECS = 1.2°C ± 0.2°C per W/m^2, including the amplifications from disappearing ice sheets and non-CO_2 GHGs (Sec. 4.4). Aerosols reduce equilibrium warming to about 8°C. Equilibrium sea level change is + 60 m (about 200 feet).").

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

[24] National Oceanic and Atmospheric Administration Global Monitoring Laboratory, *The NOAA Annual Greenhouse Gas Index (AGGI)* (*last visited* 11 June 2023) ("For example, the atmospheric abundance of CO_2 has increased by an average of 1.88 ppm per year over the past 42 years (1979-2021). This increase in CO_2 is accelerating — while it averaged about 1.6 ppm per year in the 1980s and 1.5 ppm per year in the 1990s, the growth rate increased to 2.4 ppm per year during the last decade (2011-2021).").

[25] Vaughan A. (7 January 2022) *Record levels of greenhouse gas methane are a 'fire alarm moment'*, NEW SCIENTIST ("According to data compiled by the US National Oceanic and Atmospheric Administration (NOAA), average atmospheric concentrations of methane reached a record 1900 parts per billion (ppb) in September 2021, the highest in nearly four decades of records. The figure stood at 1638 ppb in 1983.").

[26] World Meteorological Organization (26 October 2022) *The State of Greenhouse Gases in the Atmosphere Based on Global Observations through 2021*, WMO GREENHOUSE GAS BULLETIN, 1 ("In 2020 and 2021, the global network of the WMO Global Atmosphere Watch (GAW) Programme detected the largest within-year increases (15 and 18 ppb, respectively) of atmospheric methane (CH_4) since systematic measurements began in the early 1980s (Figure 1). The causes of these exceptional increases are still being investigated by the global greenhouse gas science community. Analyses of measurements of the abundances of atmospheric CH_4 and its stable carbon isotope ratio $^{13}C/^{12}C$ (reported as $\delta^{13}C(CH_4)$) (Figure 2) indicate that the increase in CH_4 since 2007 is associated with biogenic processes, but the relative contributions of anthropogenic and natural sources to this increase are unclear. While all conceivable efforts to reduce CH_4 emissions should be employed, this is not a substitute for reducing CO_2 emissions, whose impact on climate will continue for millennia."). *See also* United States Department of Commerce, *Global Monitoring Laboratory - Carbon Cycle Greenhouse Gases* (*last visited* 11 June 2023); *and* Allen G. H. (2022) *Cause of the 2020 surge in atmospheric methane clarified*, NATURE 612(7940): 413–414, 413 ("Its atmospheric concentration has nearly tripled since pre-industrial times, from 700 parts per billion (p.p.b.) to more than 1,900 p.p.b. today[3] (see also go.nature.com/3xm1dx4). During 2007–19, the concentration rose at a rate of 7.3 ± 2.4 p.p.b. per year. Then, in 2020, the methane growth rate increased dramatically to 15.1 ± 0.4 p.p.b. per year… The concentration of atmospheric

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methane surged again (see go.nature.com/3xm1dx4) too 18.2 ± 0.5 p.p.b. per year in 2021 — another mysterious acceleration without a clear cause, and the fastest rate of increase ever recorded.”).

[27] Peng S., Lin X., Thompson R. L., Xi Y., Liu G., Hauglustaine D., Lan X., Poulter B., Ramonet M., Saunois M., Yin Y., Zhang Z., Zheng B., & Ciais P. (2022) *Wetland emission and atmospheric sink changes explain methane growth in 2020*, NATURE 612(7940): 477–482, 481 (“In summary, our results show that an increase in wetland emissions, owing to warmer and wetter conditions over wetlands, along with decreased OH, contributed to the soaring methane concentration in 2020. The large positive MGR anomaly in 2020, partly due to wetland and other natural emissions, reminds us that the sensitivity of these emissions to interannual variation in climate has had a key role in the renewed growth of methane in the atmosphere since 2006. The wetland methane–climate feedback is poorly understood, and this study shows a high interannual sensitivity that should provide a benchmark for future coupled CH_4 emissions–climate models. We also show that the decrease in atmospheric CH_4 sinks, which resulted from a reduction of tropospheric OH owing to less NO_x emissions during the lockdowns, contributed 53 ± 10% of the MGR anomaly in 2020 relative to 2019. Therefore, the unprecedentedly high methane growth rate in 2020 was a compound event with both a reduction in the atmospheric CH_4 sink and an increase in Northern Hemisphere natural sources. With emission recovery to pre-pandemic levels in 2021, there could be less reduction in OH. The persistent high MGR anomaly in 2021 hints at mechanisms that differ from those responsible for 2020, and thus awaits an explanation.”). *See also* Qu Z., Jacob D. J., Zhang Y., Shen L., Varon D. J., Lu X., Scarpelli T., Bloom A., Worden J., & Parker R. J. (2022) *Attribution of the 2020 surge in atmospheric methane by inverse analysis of GOSAT observations*, ENVIRON. RES. LETT. 17(9): 094003, 1–8, 6 (“The inversion shows an increase in the methane growth rate from 28 Tg a^{-1} in 2019 to 59 Tg a^{-1} in 2020, consistent with observations. This implies a forcing on the methane budget away from a steady state by 36 Tg a−1 from 2019 to 2020, 86% (82 ± 18% in the nine-member inversion ensemble) of which is from the increase in emissions between the two years and the rest is from the decrease in tropospheric OH. Changes in methane mass offset the forcing by 5 Tg a^{-1} . The global mean OH concentration decreases by 1.2% (1.6 ± 1.5%) from 2019 to 2020, which could be due to reduced NOx emissions from COVID-19 decreases in economic activity but accounts for only a small fraction of the methane surge. We find that half of the increase in methane emissions from 2019 to 2020 is due to Africa. High precipitation and flooding in East Africa leading to increased wetland methane emissions could explain the increase. We also find a large relative increase in Canadian emissions, also apparently driven by wetlands.”).

[28] National Oceanic and Atmospheric Administration (5 April 2023) *Greenhouse gases continued to increase rapidly in 2022* (“Atmospheric methane, which is far less abundant but much more potent than CO_2 at trapping heat in the atmosphere, increased to an average of 1,911.9 parts per billion (ppb). The 2022 methane increase was 14.0 ppb, the fourth-largest annual increase recorded since NOAA’s systematic measurements began in 1983, and follows record growth in 2020 and 2021. Methane levels in the atmosphere are now more than two and a half times their pre-industrial level.”). *See also* National Oceanic and Atmospheric Administration Global Monitoring Laboratory, *Global CH_4 Monthly Means* (*last visited* 11 June 2023) (Preliminary data posted on 5 April 2023 showed atmospheric CH_4 concentrations in December 2022 reached 1924.99 ppb compared with 1908.84 ppb in December 2021.).

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

[30] Loeb N. G., Johnson G. C., Thorsen T. J., Lyman J. M., Rose F. G., & Kato S. (2021) *Satellite and Ocean Data Reveal Marked Increase in Earth’s Heating Rate*, GEOPHYS. RES. LETT. 48(13): 1–8, 1 (“Marked decreases in clouds and sea-ice and increases in trace gases and water vapor combine to increase the rate of planetary heat uptake.”), *discussed in* Bekiempis V. (17 June 2021) *Earth is trapping ‘unprecedented’ amount of heat, Nasa says*, THE GUARDIAN. *See also* von Schuckmann K., *et al.* (2023) *Heat stored in the Earth system 1960–2020: where does the energy go?*, EARTH SYST. SCI. DATA 15(4): 1675–1709, 1694 (“In IPCC AR6, the total heat rate has been assessed by 0.57 (0.43 to 0.72) W m^{-2} for the period 1971–2018 and 0.79 (0.52 to 1.06) W m^{-2} for the period 2006–2018 (Forster

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et al., 2021). Consistently, we further infer a total heating rate of 0.76 ± 0.2 W m^{-2} for the most recent era (2006–2020). Thus, the rate of heat accumulation across the Earth system has increased during the most recent era as compared to the long-term estimate – an outcome which reconfirms the earlier finding in von Schuckmann et al. (2020) and which had then been concurrently and independently confirmed in Foster et al. (2021), Hakuba et al. (2021), Loeb et al. (2021), Liu et al. (2020), Raghuraman et al. (2021), and Kramer et al. (2021). The drivers of a larger EEI in the 2000s than in the long-term period since 1971 are still unclear, and several mechanisms are discussed in literature. For example, Loeb et al. (2021) argue for a decreased reflection of energy back into space by clouds (including aerosol cloud interactions) and sea ice and increases in well-mixed greenhouse gases (GHG) and water vapor to account for this increase in EEI. Kramer et al. (2021) refer to a combination of rising concentrations of well-mixed GHG and recent reductions in aerosol emissions to be accounting for the increase, and Liu et al. (2020) address changes in surface heat flux together with planetary heat redistribution and changes in ocean heat storage.").

[31] University College London (28 September 2020) *66 Million Years of Earth's Climate Changes Revealed in Unprecedented Detail From Ocean Sediments*, SCITECHDAILY ("Co-author Dr. Anna Joy Drury (UCL Earth Sciences), said: "We use CENOGRID to understand what Earth's normal range of natural climate change and variability is and how quickly Earth recovered from past events. While we show that the Earth previously experienced warm climate states, these were characterized by extreme climate events and were radically different from our modern world. Since the peak warmth of the Hothouse, Earth's climate has gradually cooled over the last 50 million years, but the present and predicted rapid anthropogenic changes reverse this trend and, if unabated, far exceed the natural variability of the last 66 million years. CENOGRID's window into the past provides context for the ongoing anthropogenic change and how exceptional it is.""), *discussing* Westerhold T., *et al.* (2020) *An astronomically dated record of Earth's climate and its predictability over the last 66 million years*, SCIENCE 369(6509): 1383–1387.

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

[33] Carbon Brief (4 August 2022) *Mapped: How climate change affects extreme weather around the world* ("Of the attribution studies included here, scientists found that human-caused climate change has altered the likelihood or severity of an extreme weather event in 80% of cases studied (71% made more severe or likely and 9% made less so).").

[34] Intergovernmental Panel on Climate Change (2021) *Summary for Policymakers*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), SPM-10 ("It is *virtually certain* that hot extremes (including heatwaves) have become more frequent and more intense across most land regions since the 1950s, while cold extremes (including cold waves) have become less frequent and less severe, with *high confidence* that human-induced climate change is the main driver[14] of these changes. Some recent hot extremes observed over the past decade would have been *extremely unlikely* to occur without human influence on the climate system. Marine heatwaves have approximately doubled in frequency since the 1980s (*high confidence*), and human influence has *very likely* contributed to most of them since at least 2006."). *See also* Kotz M., Wenz L., & Levermann A. (2021) *Footprint of greenhouse forcing in daily temperature variability*, PROC. NAT'L. ACAD. SCI. 118(32): 1–8, 1 ("Assessing historical changes to daily temperature variability in comparison with those from state-of-the-art climate models, we show that variability has changed with distinct global patterns over the past 65 years, changes which are attributable to rising concentrations of greenhouse gases. If these rises continue, temperature variability is projected to increase by up to 100% at low latitudes and decrease by 40% at northern high latitudes by the end of the century.").

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[35] United Nations (27 July 2023) *Hottest July ever signals 'era of global boiling has arrived' says UN chief* ("Speaking at UN Headquarters, the Secretary-General underscored the need for global action on emissions, climate adaptation and climate finance. He warned that "the era of global warming has ended" and "the era of global boiling has arrived." Although climate change is evident, "we can still stop the worst," he said. "But to do so we must turn a year of burning heat into a year of burning ambition."").

[36] Fischer E. M., Sippel S., & Knutti R. (2021) *Increasing probability of record-shattering climate extremes*, NAT. CLIM. CHANGE 11: 689–685, 689 ("Here, we show models project not only more intense extremes but also events that break previous records by much larger margins. These record-shattering extremes, nearly impossible in the absence of warming, are likely to occur in the coming decades. We demonstrate that their probability of occurrence depends on warming rate, rather than global warming level, and is thus pathway-dependent. In high-emission scenarios, week-long heat extremes that break records by three or more standard deviations are two to seven times more probable in 2021–2050 and three to 21 times more probable in 2051–2080, compared to the last three decades. In 2051–2080, such events are estimated to occur about every 6–37 years somewhere in the northern midlatitudes.").

[37] Fischer E. M., Sippel S., & Knutti R. (2021) *Increasing probability of record-shattering climate extremes*, NAT. CLIM. CHANGE 11: 689–685, Supplementary Information ("In the main manuscript, we illustrate a fundamental difference in the behavior of (i) the statistically expected return levels or return periods of extremes traditionally defined as anomalies relative to a reference period, i.e. the probability of exceeding a fixed threshold and (ii) the expected probability of record-shattering extremes. For (i) the statistically expected return periods and levels are largely proportional to the warming level independent of the emission pathway (RCP/SSP), whereas for (ii) the statistically expected probability differs for the same warming level depending on the warming rate of the underlying forced response (i.e. the multi-member mean warming) and thereby on the emission pathway (RCP or SSP).").

[38] Haustein K. (2023) *Record warm July 2023*, Universität Leipzig, 1 ("However, the fact that July is the warmest month with respect to absolute global average temperatures, we just lived through the warmest of any months over the last couple hundreds or thousands of years. We may have to go back all the way to the Eemian warm period (~120.000 years ago) to find similarly warm conditions. But since paleo temperature records (so called climate proxies) do not provide high enough temporal resolution, we cannot say with certainty that this July hasn't been hotter during the peak of the current interglacial."). *See also* Paddison L. (27 July 2023) *This month is the planet's hottest on record by far – and hottest in around 120,000 years, scientists say*, CNN ("We have just lived through the hottest three-week-period on record – and almost certainly in more than a hundred thousand years.… The data used to track these records goes back to 1940, but many scientists – including those at Copernicus – say it's almost certain that these temperatures are the warmest the planet has seen in 120,000 years, given what we know from millennia of climate data extracted from tree rings, coral reefs and deep sea sediment cores.").

[39] Copernicus Climate Change Service (27 July 2023) *July 2023 sees multiple global temperature records broken* ("The month started with the daily global mean surface air temperature record being broken on four days in a row, from 3-6 July. All days since then have been hotter than the previous record of 16.80°C, set on 13 August 2016. The hottest day was 6 July, when the global average temperature reached 17.08°C, and the values recorded on 5 and 7 July were within 0.01°C of this. This means that the first three weeks of the month was the warmest three-week period on record. During the first and third weeks, temperatures also temporarily exceeded the 1.5°C threshold above preindustrial level – a limit set in the Paris Agreement. ERA5 data also show that the global mean surface air temperature for the first 23 days of July was 16.95°C. This is well above the 16.63°C recorded for the full month of July 2019, which is the current hottest July and hottest month in the ERA5 record. It is almost certain that, in due course, data will show July 2023 to break both these records."). *See also* Climate Reanalyzer (13 July 2023) *Daily 2-meter Air Temperature*, Climate Change Institute, University of Maine; *and* World Meteorological Organization (27 July 2023) *July 2023 is set to be the hottest month on record*, Press Release.

[40] World Weather Attribution (25 July 2023) *Extreme heat in North America, Europe and China in July 2023 made much more likely by climate change* ("In line with what has been expected from past climate projections and IPCC reports these events are not rare anymore today. North America, Europe and China have experienced heatwaves

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increasingly frequently over the last years as a result of warming caused by human activities, hence the current heat waves are not rare in today's climate with an event like the currently expected approximately once every 15 years in the US/Mexico region, once every 10 years in Southern Europe, and once in 5 years for China. Without human induced climate change these heat events would however have been extremely rare. In China it would have been about a 1 in 250 year event while maximum heat like in July 2023 would have been virtually impossible to occur in the US/Mexico region and Southern Europe if humans had not warmed the planet by burning fossil fuels. In all the regions a heatwave of the same likelihood as the one observed today would have been significantly cooler in a world without climate change. Similar to previous studies we found that the heatwaves defined above are 2.5°C warmer in Southern Europe, 2°C warmer in North America and about 1°C in China in today's climate than they would have been if it was not for human-induced climate change.").

[41] Philip S. Y., *et al.* (2021) *Rapid attribution analysis of the extraordinary heatwave on the Pacific Coast of the US and Canada*, WORLD WEATHER ATTRIBUTION, 26 ("In this study, the influence of human-induced climate change on the intensity and probability of the Pacific Northwest heatwave of 2021 was investigated. We analysed the heat in the area 45 ◦N–52 ◦N, 119 ◦W–123 ◦W that includes the cities Vancouver, Seattle and Portland. Based on the analysis of annual maximum daily maximum temperatures in weather observations and modeling, we conclude that the occurrence of a heatwave of the intensity experienced in that area would have been virtually impossible without human-caused climate change. Such an event is estimated to be a one in 1000-yr event in the current climate and would have been at least 150 times rarer without human-induced climate change. Also, this heatwave was about 2 ◦C (1.2 ◦C to 2.8 ◦C) hotter due to human induced climate change. Looking into the future to a world with 2 ◦C of global warming, an event like this, currently estimated to occur only once every 1000 years, would occur roughly every 5 to 10 years.").

[42] World Weather Attribution (21 December 2022) *Climate change made record breaking early season heat in Argentina and Paraguay about 60 times more likely* ("The 2022 heatwave has led to large-scale power outages, wildfires and, in combination with the ongoing drought, poor harvests. It is estimated to have led to an increase in heat-related deaths, with the impacts unequally distributed across In different cities and municipalities across South America, people living in some areas – often poorer neighbourhoods – experience higher temperatures than others, as they lack green space, adequate thermal insulation from heat, electricity, shade, and water which can be lifelines during heatwaves…. We find that human-caused climate change made the event about 60 times more Alternatively, a heatwave with a similar probability would be about 1.4°C less hot in a world that had not been warmed by human activities."), *discussing* Rivera J. A., *et al.* (2022) CLIMATE CHANGE MADE RECORD BREAKING EARLY SEASON HEAT IN ARGENTINA AND PARAGUAY ABOUT 60 TIMES MORE LIKELY, World Weather Attribution.

[43] World Meteorological Organization (2023) STATE OF THE CLIMATE IN LATIN AMERICA AND THE CARIBBEAN 2022, No. 1322, 17 ("The prolonged dry conditions associated with high temperatures led to record wildfires in January and February in Argentina and Paraguay. There was an increase of 283% and 258%, respectively, in the number of hotspots detected when compared to the 2001–2021 average.61 From January to March 2022, wildfire emissions were the highest in the last 20 years in Paraguay and northern Argentina.").

[44] Harrington L. J., Ebi K. L., Frame D. J., & Otto F. E. L. (2022) *Integrating attribution with adaptation for unprecedented future heatwaves*, CLIM. CHANGE 172(2): 1–7, 3 ("Thus, specifically resolving whether a recent heatwave — say, one which occurs once per decade in today's climate — would have occurred either once in 100 generations or once in 1000 generations in a pre-industrial climate, is no longer useful. When the current climate has changed so significantly that the pre-industrial world becomes a poor basis of comparison, other tools are needed to instead quantify future changes in exposure or the effectiveness of adaptation to changes in extreme weather seen over recent decades."), *discussed in* Sengupta S. (3 May 2022) *An extraordinary heat wave exposes the limits of protecting people*, THE NEW YORK TIMES ("For more than a month now, across much of the country (and in next door Pakistan), temperatures have soared and stayed there. The capital, Delhi, topped 46 degrees Celsius (114 degrees Fahrenheit) last week. West Bengal, in the muggy east of the country, where my family is from, is among those regions where the combination of heat and humidity could rise to a threshold where the human body is in fact at risk of cooking itself. That theoretical limit is a "wet bulb" temperature — when a thermometer is wrapped in a wet cloth, accounting for both heat and humidity — of 35 degrees Celsius. In neighboring Pakistan, the Meteorological Department warned last

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week that daily high temperatures were 5 to 8 degrees Celsius above normal, and that in the mountainous north, fast-melting snow and ice could cause glacial lakes to burst. How much of this extreme heat can be blamed on climate change? That's now becoming an "obsolete question," Friederike Otto, a leader in the science of attributing extreme weather events to climate change, said in a paper published Monday. The rise in the average global temperature has already intensified heat waves "many times faster than any other type of extreme weather," the paper concluded. Get used to extremes. Adapt. As much as possible."); *and* Tunio Z. (7 May 2022) *An unprecedented heat wave in India and Pakistan is putting the lives of more than a billion people at risk*, Inside Climate News. *See also* Copernicus Climate Change Services (7 July 2022) *Heatwaves grip parts of Europe, Asia and North America in the first half of 2022* ("The second heatwave in this analysis, covering Pakistan and northwestern India, is the longest and the most impactful, in terms of the number of people directly affected. A series of warm spells impacted nearly 2 billion people throughout the whole season; some areas are still experiencing exceptional temperatures as of mid-June, with the most anomalous temperatures observed in northeastern India, and the monsoon approaching northwestern India more slowly than usual.").

[45] First Street Foundation (2022) The 6th National Risk Assessment: *Hazardous Heat*, 4 ("The results indicate that the incidence of extreme heat is growing across the country, both in absolute and relative terms. In absolute terms, the incidence of heat that exceeds the threshold of the National Weather Service's (NWS) highest category for heat, called "Extreme Danger" (Heat Index above 125°F) is expected to impact about 8 million people this year, increasing to about 107 million people in 2053, an increase of 13 times over 30 years. This increase in "Extreme Danger Days" is concentrated in the middle of the country, in areas where there are no coastal influences to mitigate extreme temperatures."), *discussed in* Kaufman L. (15 August 2022) *Much of the US Will Be an 'Extreme Heat Belt' by the 2050s*, Bloomberg.

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

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

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[48] World Meteorological Organization (2023) State of the Climate in Latin America and the Caribbean 2022, No. 1322, 15–16 (“Drought also affected the west coast of subtropical South America, including Chile, where the last year with above average rainfall was 2006.51 The year 2022 was the fourth-driest year on record for Chile, which is experiencing a 14-year-long megadrought, the region’s longest and most severe drought in more than 1 000 years.”).

[49] World Meteorological Organization (2022) State of the Climate in Latin America and the Caribbean 2021, No. 1295, 14 (“The 2021 Atlantic hurricane season was very active, with 21 named storms – well above the 1981–2010 average of 14 – including seven hurricanes, of which four were major hurricanes. With about US$ 80 billion in damage (much of which occurred in the United States of America, associated with Hurricane Ida), it was also one of the costliest seasons. It was the sixth consecutive above-normal Atlantic hurricane season and the seventh consecutive year with a named storm forming before the official start to the season on 1 June (Tropical Storm Ana formed on 22 May). On 30 June, Tropical Storm Elsa (later Hurricane Elsa) became the earliest fifth named storm on record. Hurricane Elsa would become the first hurricane of the season on 2 July, and affected several territories in the Caribbean, including Barbados, Saint Lucia, Saint Vincent and the Grenadines, Martinique, the Dominican Republic, Haiti, Jamaica, the Cayman Islands and Cuba, before moving into Florida/United States.[26]”).

[50] World Meteorological Organization (2022) State of the Climate in Latin America and the Caribbean 2021, No. 1295, 14 (“The 2021 Atlantic hurricane season was very active, with 21 named storms – well above the 1981–2010 average of 14 – including seven hurricanes, of which four were major hurricanes. With about US$ 80 billion in damage (much of which occurred in the United States of America, associated with Hurricane Ida), it was also one of the costliest seasons. It was the sixth consecutive above-normal Atlantic hurricane season and the seventh consecutive year with a named storm forming before the official start to the season on 1 June (Tropical Storm Ana formed on 22 May). On 30 June, Tropical Storm Elsa (later Hurricane Elsa) became the earliest fifth named storm on record. Hurricane Elsa would become the first hurricane of the season on 2 July, and affected several territories in the Caribbean, including Barbados, Saint Lucia, Saint Vincent and the Grenadines, Martinique, the Dominican Republic, Haiti, Jamaica, the Cayman Islands and Cuba, before moving into Florida/United States.[26]”).

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

[52] Intergovernmental Panel on Climate Change (2022) *Summary for Policymakers*, *in* Climate Change 2022: Mitigation of Climate Change, *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Shukla P. R., Skea J., Slade R., Al Khourdajie A., van Diemen R., McCollum D., Pathak M., Some S., Vyas P., Fradera R., Belkacemi M., Hasija A., Lisboa G., Luz S., & Malley J. (eds.), 24 (“In modelled global low emission pathways, the projected reduction of cooling and warming aerosol emissions over time leads to net warming in the near- to mid-term. In these mitigation pathways, the projected reductions of cooling aerosols are mostly due to reduced fossil fuel combustion that was not equipped with effective air pollution controls.”). *See also* Szopa S., Naik V., Adhikary B., Artaxo P., Berntsen T., Collins W. D., Fuzzi S., Gallardo L., Kiendler-Scharr A., Klimont Z., Liao H., Unger N., & Zanis P. (2021) *Chapter 6: Short-lived climate forcers*, in Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 822 (“Additional methane and BC mitigation would contribute to offsetting the additional warming associated with SO_2 reductions that would accompany decarbonization (*high confidence*).”); Ramanathan V. & Feng Y. (2008) *On avoiding dangerous anthropogenic interference with the climate system: Formidable challenges ahead*, Proc. Nat’l. Acad. Sci. 105(38): 14245–14250, 14248 (“Switching from coal to ‘‘cleaner’’ natural gas will reduce CO_2 emission and thus would be effective in minimizing future increases in the committed warming. However, because it also

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reduces air pollution and thus the ABC [Atmospheric Brown Cloud] masking effect, it may speed up the approach to the committed warming of 2.4°C (1.4–4.3°C).”); United Nations Environment Programme & World Meteorological Organization (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone, 254 (“Evaluating global mean temperature change, it was found that the targeted measures to reduce emissions of methane and BC could greatly reduce warming rates over the next few decades (Figure 6.1; Box 6.1). When all measures are fully implemented, warming during the 2030s relative to the present would be only half as much as in the reference scenario. In contrast, even a fairly aggressive strategy to reduce CO_2 emissions, as for the CO_2-measures scenario, does little to mitigate warming until after the next 20-30 years (Box 6.2). In fact, sulphur dioxide (SO_2) is coemitted with CO_2 in some of the most highly emitting activities, coal burning in large-scale combustion such as in power plants, for example, that are obvious targets for reduced usage under a CO_2-emissions mitigation strategy. Hence such strategies can lead to additional near-term warming (Figure 6.1), in a well-known temporary effect (e.g. Raes and Seinfeld, 2009), although most of the near-term warming is driven by CO_2 emissions in the past. The CO_2-measures scenario clearly leads to long-term benefits however, with a dramatically lower warming rate at 2070 under that scenario than under the scenario with only CH_4 and BC measures (see Figure 6.1 and timescales in Box 6.2). Hence the near-term measures clearly cannot be substituted for measures to reduce emissions of long-lived GHGs. The near-term measures largely target different source sectors for emissions than the CO_2 measures, so that the emissions reductions of the short-lived pollutants are almost identical regardless of whether the CO_2 measures are implemented or not, as shown in Chapter 5. The near-term measures and the CO_2 measures also impact climate change over different timescales owing to the different lifetimes of these substances. In essence, the near-term CH_4 and BC measures are effectively uncoupled from CO_2 measures examined here.”); *and* Wanser K., Wong A., Karspeck A., & Esguerra N. (2023) Near-term Climate Risk and Intervention: *A Roadmap for Research, U.S. Research Investment, and International Scientific Cooperation*, SilverLining, 12 (“Particles (i.e., aerosols) in the atmosphere generally increase the total amount of sunlight reflected to space by scattering incoming sunlight. Anthropogenic activities produce both GHGs and other particulate matter; while GHGs warm climate, aerosols have a cooling effect both by directly scattering sunlight (i.e., the aerosol direct effect) and indirectly as the aerosols interact with clouds, increasing their brightness and/or their duration (i.e., the cloud–aerosol effect) … The potential global cooling effect of all anthropogenic aerosols is estimated at 0.5–1.1℃ (see Figure 6). Thus, these effects are potentially very large while also serving as a large source of uncertainty, making reducing these uncertainties among the highest priorities for climate research, particularly in the context of assessing near-term climate risk. Particles from emissions produced by human activities are also associated with significant adverse health and environmental effects. Actions are ongoing around the world to substantially reduce them, including recent regulation to substantially reduce sulfate emissions from ships. As the world reduces these particulate emissions, the loss of this cooling “shield” could lead to rapid substantial warming.”).

[53] International Energy Agency (2023) Credible pathways to 1.5 °C - Four pillars for action in the 2020s, 1–15, 3, 11 (“In the energy sector, decarbonising electricity, accelerating energy efficiency and electrification are the critical tools. Capacity additions of renewables need to triple from 2022 levels by 2030, reaching around 1200 GW annually, representing on average 90% of new generation capacity each year. Electric car sales should reach a market share of around 60% by 2030, while zero emissions medium and heavy freight trucks should reach a market share of around 35% by the same year. Reducing deforestation to net zero by 2030 – in line with The Glasgow Leaders’ Declaration on Forests and Land Use – provides the largest share of CO_2 emissions reductions from the land-use sector. Tackling non-CO_2 emissions is vital to limiting peak warming. Assuming strong action on CO_2, meeting or exceeding commitments like the Kigali Amendment on HFCs and the Global Methane Pledge, and acting on non-CO_2 emissions from agriculture, could make the difference between a scenario which substantially overshoots 1.5 °C, risking triggering irreversible climate tipping points, and one which does not. Even in a low overshoot scenario, carbon capture and storage and atmospheric carbon dioxide removal will be required to mitigate and compensate hard-to-abate residual emissions. Projects capturing around 1.2 Gt CO_2 by 2030 need to be implemented, against the roughly 0.3 Gt CO_2 currently planned for 2030. A credible pathway to the 1.5 °C goal needs strong, immediate action on each of these four pillars, to deliver immediate and rapid emissions reductions; strong contributions from all countries, especially advanced and major economies; and clear policy signals to enable actors to anticipate and achieve change. … Methane is responsible for around 30% of the rise in global temperatures since the Industrial Revolution, and cutting methane emissions in the NZE Scenario has the single biggest impact after CO_2 on limiting the temperature rise to 2050. One hundred and fifty countries have now joined the Global Methane Pledge, which was launched at COP26 in 2021 and aims to reduce methane emissions from human activity by at least 30% from 2020 levels by 2030.

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

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

[55] Armstrong McKay D. I., Staal A., Abrams J. F., Winkelmann R., Sakschewski B., Loriani S., Fetzer I., Cornell S. E., Rockström J., & Lenton T. M. (2022) *Exceeding 1.5°C global warming could trigger multiple climate tipping points*, SCIENCE 377(6611): 1–10, 7 ("The chance of triggering CTPs is already non-negligible and will grow even with stringent climate mitigation (SSP1-1.9 in Fig. 2, B and C). Nevertheless, achieving the Paris Agreement's aim to pursue efforts to limit warming to 1.5°C would clearly be safer than keeping global warming below 2°C (90) (Fig. 2). Going from 1.5 to 2°C increases the likelihood of committing to WAIS and GrIS collapse near complete warm-water coral die-off, and abrupt permafrost thaw; further, the best estimate threshold for LABC collapse is crossed. The likelihood of triggering AMOC collapse, Boreal forest shifts, and extra-polar glacier loss becomes non-negligible at >1.5°C and glacier loss becomes likely by ~2°C. A cluster of abrupt shifts occur in ESMs at 1.5 to 2°C (19). Although not tipping elements, ASSI loss could become regular by 2°C, gradual permafrost thaw would likely become widespread beyond 1.5°C, and land carbon sink weakening would become significant by 2°C."). *See also* Lenton T. M., Rockstrom J., Gaffney O., Rahmstorf S., Richardson K., Steffen W., & Schellnhuber H. J. (2019) *Climate tipping points—too risky to bet against*, Comment, NATURE 575(7784): 592–595, 594 ("In our view, the clearest emergency would be if we were approaching a global cascade of tipping points that led to a new, less habitable, 'hothouse' climate state[11]. Interactions could happen through ocean and atmospheric circulation or through feedbacks that increase greenhouse-gas levels and global temperature. Alternatively, strong cloud feedbacks could cause a global tipping point[12,13].We argue that cascading effects might be common. Research last year[14] analysed 30 types of regime shift spanning physical climate and ecological systems, from collapse of the West Antarctic ice sheet to a switch from rainforest to savanna. This indicated that exceeding tipping points in one system can increase the risk of crossing them in others. Such links were found for 45% of possible interactions[14]. In our view, examples are starting to be observed. … If damaging tipping cascades can occur and a global tipping point cannot be ruled out, then this is an existential threat to civilization. No amount of economic cost–benefit analysis is going to help us. We need to change our

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approach to the climate problem. … In our view, the evidence from tipping points alone suggests that we are in a state of planetary emergency: both the risk and urgency of the situation are acute….”); Steffen W., *et al*. (2018) *Trajectories of the Earth System in the Anthropocene*, PROC. NAT'L. ACAD. SCI. 115(33): 8252–8259, 8254 (“This analysis implies that, even if the Paris Accord target of a 1.5 °C to 2.0 °C rise in temperature is met, we cannot exclude the risk that a cascade of feedbacks could push the Earth System irreversibly onto a “Hothouse Earth” pathway. The challenge that humanity faces is to create a “Stabilized Earth” pathway that steers the Earth System away from its current trajectory toward the threshold beyond which is Hothouse Earth (Fig. 2). The human-created Stabilized Earth pathway leads to a basin of attraction that is not likely to exist in the Earth System's stability landscape without human stewardship to create and maintain it. Creating such a pathway and basin of attraction requires a fundamental change in the role of humans on the planet. This stewardship role requires deliberate and sustained action to become an integral, adaptive part of Earth System dynamics, creating feedbacks that keep the system on a Stabilized Earth pathway (Alternative Stabilized Earth Pathway).”); *and* Intergovernmental Panel on Climate Change (2023) AR6 SYNTHESIS REPORT: CLIMATE CHANGE 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 36, 42 (“In terrestrial ecosystems, 3–14% of the tens of thousands of species assessed will likely face a very high risk of extinction at a GWL of 1.5°C. Coral reefs are projected to decline by a further 70–90% at 1.5°C of global warming (*high confidence*). At this GWL, many low-elevation and small glaciers around the world would lose most of their mass or disappear within decades to centuries (*high confidence*). Regions at disproportionately higher risk include Arctic ecosystems, dryland regions, small island development states and Least Developed Countries (*high confidence*). … The likelihood of abrupt and irreversible changes and their impacts increase with higher global warming levels (*high confidence*). As warming levels increase, so do the risks of species extinction or irreversible loss of biodiversity in ecosystems such as forests (*medium confidence*), coral reefs (*very high confidence*) and in Arctic regions (*high confidence*). Risks associated with large-scale singular events or tipping points, such as ice sheet instability or ecosystem loss from tropical forests, transition to high risk between 1.5°C–2.5°C (*medium confidence*) and to very high risk between 2.5°C–4°C (*low confidence*). The response of biogeochemical cycles to anthropogenic perturbations can be abrupt at regional scales and irreversible on decadal to century time scales (*high confidence*). The probability of crossing uncertain regional thresholds increases with further warming (*high confidence*).”).

[56] Xu Y. & Ramanathan V. (2017) *Well below 2 °C: Mitigation strategies for avoiding dangerous to catastrophic climate changes*, PROC. NAT'L. ACAD. SCI. 114(39): 10319–10323, 10320 (“Box 2. Risk Categorization of Climate Change to Society. … [A] 2 °C warming would double the land area subject to deadly heat and expose 48% of the population. A 4 °C warming by 2100 would subject 47% of the land area and almost 74% of the world population to deadly heat, which could pose existential risks to humans and mammals alike unless massive adaptation measures are implemented, such as providing air conditioning to the entire population or a massive relocation of most of the population to safer climates. … This bottom 3 billion population comprises mostly subsistent farmers, whose livelihood will be severely impacted, if not destroyed, with a one- to five-year megadrought, heat waves, or heavy floods; for those among the bottom 3 billion of the world's population who are living in coastal areas, a 1- to 2-m rise in sea level (likely with a warming in excess of 3 °C) poses existential threat if they do not relocate or migrate. It has been estimated that several hundred million people would be subject to famine with warming in excess of 4 °C (54). However, there has essentially been no discussion on warming beyond 5 °C. Climate change-induced species extinction is one major concern with warming of such large magnitudes (>5 °C). The current rate of loss of species is ~1,000-fold the historical rate, due largely to habitat destruction. At this rate, about 25% of species are in danger of extinction in the coming decades (56). Global warming of 6 °C or more (accompanied by increase in ocean acidity due to increased CO_2) can act as a major force multiplier and expose as much as 90% of species to the dangers of extinction (57). The bodily harms combined with climate change-forced species destruction, biodiversity loss, and threats to water and food security, as summarized recently (58), motivated us to categorize warming beyond 5 °C as unknown??, implying the possibility of existential threats.”). *See also* Xu C., Kohler T. A., Lenton T. M., Svenning J.-C., & Scheffer M. (2020) *Future of the human climate niche*, PROC. NAT'L. ACAD. SCI. 117(21): 11350–11355, 11350 (“Here, we demonstrate that for millennia, human populations have resided in the same narrow part of the climatic envelope available on the globe, characterized by a major mode around ~11 °C to 15 °C mean annual temperature (MAT). …We show that in a business-as-usual climate change scenario, the geographical position of this temperature niche is projected to shift more over the coming 50 y than it has moved since 6000 BP. … Specifically,

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3.5 billion people will be exposed to MAT ≥29.0 °C, a situation found in the present climate only in 0.8% of the global land surface, mostly concentrated in the Sahara, but in 2070 projected to cover 19% of the global land (Fig. 3). … For instance, accounting for population growth projected in the SSP3 scenario, each degree of temperature rise above the current baseline roughly corresponds to one billion humans left outside the temperature niche, absent migration (*SI Appendix*, Fig. S14).”); Watts N., *et al.* (2021) *The 2020 report of The Lancet Countdown on health and climate change: responding to converging crises*, The Lancet 397(10269): 129–170, 129 (“Vulnerable populations were exposed to an additional 475 million heatwave events globally in 2019, which was, in turn, reflected in excess morbidity and mortality (indicator 1.1.2). During the past 20 years, there has been a 53.7% increase in heat-related mortality in people older than 65 years, reaching a total of 296 000 deaths in 2018 (indicator 1.1.3). The high cost in terms of human lives and suffering is associated with effects on economic output, with 302 billion h of potential labour capacity lost in 2019 (indicator 1.1.4). India and Indonesia were among the worst affected countries, seeing losses of potential labour capacity equivalent to 4–6% of their annual gross domestic product (indicator 4.1.3).”); Atwoli L., *et al.* (2021) *Call for emergency action to limit global temperature increases, restore biodiversity, and protect health*, The Lancet 398(10304): 939–941, 939 (“Harms disproportionately affect the most vulnerable, including children, older populations, ethnic minorities, poorer communities, and those with underlying health problems.”); Intergovernmental Panel on Climate Change (2023) AR6 Synthesis Report: Climate Change 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 36 (“In terrestrial ecosystems, 3–14% of the tens of thousands of species assessed will likely face a very high risk of extinction at a GWL of 1.5°C. Coral reefs are projected to decline by a further 70–90% at 1.5°C of global warming (*high confidence*). At this GWL, many low-elevation and small glaciers around the world would lose most of their mass or disappear within decades to centuries (*high confidence*). Regions at disproportionately higher risk include Arctic ecosystems, dryland regions, small island development states and Least Developed Countries (*high confidence*).”); *and* Berwyn B. (14 February 2023) *Sea Level Rise Could Drive 1 in 10 People from Their Homes, with Dangerous Implications for International Peace, UN Secretary General Warns*, Inside Climate News.

[57] Intergovernmental Panel on Climate Change (2021) *Summary for Policymakers*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 15 (“With every additional increment of global warming, changes in extremes continue to become larger. For example, every additional 0.5°C of global warming causes clearly discernible increases in the intensity and frequency of hot extremes, including heatwaves (*very likely*), and heavy precipitation (*high confidence*), as well as agricultural and ecological droughts in some regions (*high confidence*). Discernible changes in intensity and frequency of meteorological droughts, with more regions showing increases than decreases, are seen in some regions for every additional 0.5°C of global warming (*medium confidence*). Increases in frequency and intensity of hydrological droughts become larger with increasing global warming in some regions (*medium confidence*). There will be an increasing occurrence of some extreme events unprecedented in the observational record with additional global warming, even at 1.5°C of global warming. Projected percentage changes in frequency are higher for rarer events (*high confidence*).”). *See also* Fischer E. M., Sippel S., & Knutti R. (2021) *Increasing probability of record-shattering climate extremes*, Nat. Clim. Change 11: 689–695, 689 (“Here, we show models project not only more intense extremes but also events that break previous records by much larger margins. These record-shattering extremes, nearly impossible in the absence of warming, are likely to occur in the coming decades. We demonstrate that their probability of occurrence depends on warming rate, rather than global warming level, and is thus pathway-dependent. In high-emission scenarios, week-long heat extremes that break records by three or more standard deviations are two to seven times more probable in 2021–2050 and three to 21 times more probable in 2051–2080, compared to the last three decades.”).

[58] Goldstein A., Noon M. L., Ledezma J. C., Roehrdanz P. R., Raghav S., McGreevey M., Stone C., Shrestha S., Golden Kroner R., Hole D., & Turner W. (2021) Irrecoverable Carbon: *The Places We Must Protect to Avert Climate Catastrophe*, Conservation International, 7 (“‘Irrecoverable carbon’ refers to the vast stores of carbon in nature that are vulnerable to release from human activity and, if lost, could not be restored by 2050 — when the world must reach net-zero emissions to avoid the worst impacts of climate change. There are high concentrations of irrecoverable carbon in the Amazon (31.5 Gt), the Congo Basin (8.1 Gt), and New Guinea (7.3 Gt). Other important

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irrecoverable carbon reserves are located in the Pacific Northwest of North America, the Valdivian forests of Chile, the mangroves and swamp forests of Guyana, the peatlands of Northern Scotland, Niger Delta's mangroves, Cambodia's Tonle Sap Lake, the Scandinavian and Siberian boreal forests, and the eucalyptus forest of Southeast Australia, among others."). *See also* Griscom B. W., *et al.* (2017) *Natural climate solutions*, Proc. Nat'l. Acad. Sci. 114(44): 11645–11650, 11645 ("Better stewardship of land is needed to achieve the Paris Climate Agreement goal of holding warming to below 2 °C; however, confusion persists about the specific set of land stewardship options available and their mitigation potential. To address this, we identify and quantify "natural climate solutions" (NCS): 20 conservation, restoration, and improved land management actions that increase carbon storage and/or avoid greenhouse gas emissions across global forests, wetlands, grasslands, and agricultural lands. We find that the maximum potential of NCS—when constrained by food security, fiber security, and biodiversity conservation—is 23.8 petagrams of CO_2 equivalent ($PgCO_2e$) y^{-1} (95% CI 20.3–37.4). This is ≥30% higher than prior estimates, which did not include the full range of options and safeguards considered here. About half of this maximum (11.3 $PgCO_2e$ y^{-1}) represents cost-effective climate mitigation, assuming the social cost of CO_2 pollution is ≥100 USD $MgCO_2e^{-1}$ by 2030. Natural climate solutions can provide 37% of cost-effective CO_2 mitigation needed through 2030 for a >66% chance of holding warming to below 2 °C. One-third of this cost-effective NCS mitigation can be delivered at or below 10 USD $MgCO_2^{-1}$. Most NCS actions—if effectively implemented—also offer water filtration, flood buffering, soil health, biodiversity habitat, and enhanced climate resilience. Work remains to better constrain uncertainty of NCS mitigation estimates. Nevertheless, existing knowledge reported here provides a robust basis for immediate global action to improve ecosystem stewardship as a major solution to climate change."); Goldstein A., *et al.* (2020) *Protecting irrecoverable carbon in Earth's ecosystems*, Nat. Clim. Change 10(4): 287–295; *and* Noon M. L., Goldstein A., Ledezma J. C., Roehrdanz P. R., Cook-Patton S. C., Spawn-Lee S. A., Wright T. M., Gonzalez-Roglich M., Hole D. G., Rockström J., & Turner W. R. (2021) *Mapping the irrecoverable carbon in Earth's ecosystems*, Nat. Sustain. 5: 37–46.

[59] Zhang Y., Held I., & Fueglistaler S. (2021) *Projections of tropical heat stress constrained by atmospheric dynamics*, Nat. Geo. 14(3): 133–137, 133 ("For each 1 °C of tropical mean warming, global climate models project extreme TW (the annual maximum of daily mean or 3-hourly values) to increase roughly uniformly between 20° S and 20° N latitude by about 1 °C. This projection is consistent with theoretical expectation based on tropical atmospheric dynamics, and observations over the past 40 years, which gives confidence to the model projection. For a 1.5 °C warmer world, the probable (66% confidence interval) increase of regional extreme TW is projected to be 1.33–1.49 °C, whereas the uncertainty of projected extreme temperatures is 3.7 times as large. These results suggest that limiting global warming to 1.5 °C will prevent most of the tropics from reaching a TW of 35 °C, the limit of human adaptation.").

[60] Lenton T. M., Xu C., Abrams J. F., Ghadiali A., Loriani S., Sakschewski B., Zimm C., Ebi K. L., Dunn R. R., Svenning J.-C., & Scheffer M. (2023) *Quantifying the human cost of global warming*, Nat. Sustain. 1–11, calculated based on Supplementary Data 1, 1, 5–6 ("Country-level results for population, land area and land fraction exposed to MAT > 29°C … By end-of-century (2080–2100), current policies leading to around 2.7 °C global warming could leave one-third (22–39%) of people outside the niche. Reducing global warming from 2.7 to 1.5 °C results in a ~5-fold decrease in the population exposed to unprecedented heat (mean annual temperature ≥29 °C). The lifetime emissions of ~3.5 global average citizens today (or ~1.2 average US citizens) expose one future person to unprecedented heat by end-of-century. That person comes from a place where emissions today are around half of the global average. These results highlight the need for more decisive policy action to limit the human costs and inequities of climate change. … Assuming a future world of 9.5 billion, India has the greatest population exposed under 2.7 °C global warming, >600 million, but this reduces >6-fold to ~90 million at 1.5 °C global warming. Nigeria has the second largest population exposed, >300 million under 2.7 °C global warming, but this reduces >7-fold to 20-fold, from ~100 million under 2.7 °C global warming to 80 million exposed under 2.7 °C global warming, there are even larger proportional reductions at 1.5 °C global warming. Sahelian–Saharan countries including Sudan (sixth ranked) and Niger (seventh) have a ~2-fold reduction in exposure, because they still have a large fraction of land area hot exposed at 1.5 °C global warming (Fig. 5b). The fraction of land area exposed approaches 100% for several countries under 2.7 °C global warming (Fig. 5b). Brazil has the greatest absolute land area exposed under 2.7 °C global warming,") despite almost no area being exposed at 1.5 °C, and Australia and India also experience massive increases in absolute area exposed (Fig. 4). (If the future population reaches 11.1 billion, the ranking of countries by population

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exposed remains similar, although the numbers exposed increase.) Those most exposed under 2.7 °C global warming come from nations that today are above the median poverty rate and below the median per capita emissions (Fig. 6).”). *See also* Xu C., Kohler T. A., Lenton T. M., Svenning J.-C., & Scheffer M. (2020) *Future of the human climate niche*, PROC. NAT'L. ACAD. SCI. 117(21): 11350–11355, 11352 (“Such a calculation suggests that for the RCP8.5 business-as-usual climate scenario, and accounting for expected demographic developments (the SSP3 scenario[15]),∼3.5 billion people (roughly 30% of the projected global population; SI Appendix, Fig. S12) would have to move to other areas if the global population were to stay distributed relative to temperature the same way it has been for the past millennia (SI Appendix, Fig. S13). Strong climate mitigation following the RCP2.6 scenario would substantially reduce the geographical shift in the niche of humans and would reduce the theoretically needed movement to ∼1.5 billion people (∼13% of the projected global population; SI Appendix, Figs. S12 and S13).”).

[61] Intergovernmental Panel on Climate Change (2022) *Summary for Policymakers*, *in* CLIMATE CHANGE 2022: MITIGATION OF CLIMATE CHANGE, *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Shukla P. R., Skea J., Slade R., Al Khourdajie A., van Diemen R., McCollum D., Pathak M., Some S., Vyas P., Fradera R., Belkacemi M., Hasija A., Lisboa G., Luz S., & Malley J. (eds.), SPM-22 (“C.1.2 In modelled pathways that limit warming to 2°C (>67%) assuming immediate action, global net CO_2 emissions are reduced compared to modelled 2019 emissions by 27% [11–46%] in 2030 and by 52% [36-70%] in 2040; and global CH_4 emissions are reduced by 24% [9–53%] in 2030 and by 37% [20–60%] in 2040. In pathways that limit warming to 1.5°C (>50%) with no or limited overshoot global net CO_2 emissions are reduced compared to modelled 2019 emissions by 48% [36–69%] in 2030 and by 80% [61-109%] in 2040; and global CH_4 emissions are reduced by 34% [21–57%] in 2030 and 44% [31-63%] in 2040. There are similar reductions of non-CO_2 emissions by 2050 in both types of pathways: CH_4 is reduced by 45% [25–70%]; N_2O is reduced by 20% [-5 – 55%]; and F-Gases are reduced by 85% [20–90%]. [FOOTNOTE 44] Across most modelled pathways, this is the maximum technical potential for anthropogenic CH_4 reductions in the underlying models (*high confidence*). Further emissions reductions, as illustrated by the IMP-SP pathway, may be achieved through changes in activity levels and/or technological innovations beyond those represented in the majority of the pathways (*medium confidence*). Higher emissions reductions of CH_4 could further reduce peak warming. (*high confidence*) (Figure SPM.5)”).

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

[63] Note that inclusion of sulfate reductions that would be expected to occur alongside reduced use of fossil fuels accounts for unmasking. Forster P. M., *et al.* (2023) *Indicators of Global Climate Change 2022: annual update of large-scale indicators of the state of the climate system and human influence*, EARTH SYST. SCI. DATA 15(6): 2295–2327, 2312–2313 (“The RCB for limiting warming to 1.5 °C is becoming very small. It is important, however, to correctly interpret this information. RCB estimates consider projected reductions in non-CO_2 emissions that are aligned with a global transition to net zero CO_2 emissions. These estimates assume median reductions in non-CO_2 emissions between 2020–2050 of CH_4 (50 %), N_2O (25 %) and SO_2 (77 %). If these non-CO_2 greenhouse gas emission reductions are not achieved, the RCB will be smaller (see Supplement, Sect. S8).”).

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[64] Forster P. M., *et al.* (2023) *Indicators of Global Climate Change 2022: annual update of large-scale indicators of the state of the climate system and human influence*, EARTH SYST. SCI. DATA 15(6): 2295–2327, 2312 ("The RCB is estimated by application of the WGI AR6 method described in Rogelj et al. (2019), which involves the combination of the assessment of five factors: (i) the most recent decade of human-induced warming, (ii) the transient climate response to cumulative emissions of CO_2 (TCRE), (iii) the zero emissions commitment (ZEC), (iv) the temperature contribution of non-CO_2 emissions and (v) an adjustment term for Earth system feedbacks that are otherwise not captured through the other factors. AR6 WGI reassessed all five terms (Canadell et al., 2021). The incorporation of factor (v) was further considered by Lamboll and Rogelj (2022).").

[65] Canadell J. G., *et al.* (2021) *Chapter 5: Global Carbon and other Biogeochemical Cycles and Feedbacks*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 739 ("The applicability of the linear feedback framework (Section 5.4.5.5) suggests that large-scale biogeochemical feedbacks are approximately linear in the forcing from changes in CO_2 and climate. Nevertheless, regionally the biosphere is known to be capable of producing abrupt changes or even 'tipping points' (Higgins and Scheiter, 2012; Lasslop et al., 2016).").

[66] Canadell J. G., *et al.* (2021) *Chapter 5: Global Carbon and other Biogeochemical Cycles and Feedbacks*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 67 ("There is *low confidence* in the estimate of the non-CO_2 biogeochemical feedbacks, due to the large range in the estimates of α for some individual feedbacks (Figure 5.29c), which can be attributed to the diversity in how models account for these feedbacks, limited process-level understanding, and the existence of known feedbacks for which there is not sufficient evidence to assess the feedback strength."). *See also* Chen D., Rojas M., Samset B. H., Cobb K., Diongue Niang A., Edwards P., Emori S., Faria S. H., Hawkins E., Hope P., Huybrechts P., Meinshausen M., Mustafa S. K., Plattner G.-K., & Tréguier A.-M. (2021) *Chapter 1: Framing, Context and Methods*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.*, 202 ("Such paleoclimate evidence has even fuelled concerns that anthropogenic GHGs could tip the global climate into a permanent hot state (Steffen et al., 2018). However, there is no evidence of such non-linear responses at the global scale in climate projections for the next century, which indicate a near-linear dependence of global temperature on cumulative GHG emissions (Section 1.3.5, Chapter 5, Section 5.5 and Chapter 7, Section 7.4.3.1). At the regional scale, abrupt changes and tipping points, such as Amazon forest dieback and permafrost collapse, have occurred in projections with Earth System Models (Drijfhout et al., 2015; Bathiany et al., 2020; Chapter 4, Section 4.7.3). In such simulations, tipping points occur in narrow regions of parameter space (e.g., CO_2 concentration or temperature increase), and for specific climate background states. This makes them difficult to predict using ESMs relying on parmeterizations of known processes. In some cases, it is possible to detect forthcoming tipping points through time-series analysis that identifies increased sensitivity to perturbations as the tipping point is approached (e.g., 'critical slowing-down', Scheffer et al., 2012)."); Bathiany S., Hidding J., & Scheffer M. (2020) *Edge Detection Reveals Abrupt and Extreme Climate Events*, J. CLIM. 33(15): 6399–6421, 6416 ("Despite their societal relevance, our knowledge about the risks of future abrupt climate shifts is far from robust. Several important aspects are highly uncertain: future greenhouse gas emissions (scenario uncertainty), the current climate state (initial condition uncertainty), the question whether and how to model specific processes (structural uncertainty), and what values one should choose for parameters appearing in the equations (parametric uncertainty). Such uncertainties can be explored using ensemble simulations. For example, by running many simulations with different combinations of parameter values a perturbed-physics ensemble can address how parameter uncertainty affects the occurrence of extreme events (Clark et al. 2006). This strategy can be particularly beneficial for studying abrupt events as well since abrupt shifts are associated with region-specific processes, whereas models are usually calibrated to produce a realistic global mean climate at the expense of regional realism (Mauritsen et al. 2012; McNeall et al. 2016). The currently available model configurations are therefore neither reliable nor sufficient to assess the risk of abrupt shifts (Drijfhout et al. 2015). It is hence very plausible that yet-undiscovered tipping points can occur in climate models."); McIntyre M. E. (2023) *Climate tipping points: A personal view*, PHYSICS TODAY 76(3), 44–49, 45–46 ("Nearly all the climate system's real complexity is outside the scope of any model, whether it's

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a global climate model that aims to represent the climate system as a whole or a model that only simulates the carbon cycle, ice flow, or another subsystem…. Changes taking only a few years are almost instantaneous from a climate-system perspective. They're a warning to take seriously the possibility of tipping points in the dynamics of the real climate system.[9] The warning is needed because some modelers have argued that tipping points are less probable for the real climate system than for the simplified, low-order climate models studied by dynamic-systems researchers.[3] Other researchers, however, have suggested that such a tipping point may be reached sometime in the next few decades or even sooner.[6,7] Some of its mechanisms resemble those of the Dansgaard–Oeschger warmings and would suddenly accelerate the rate of disappearance of Arctic sea ice. As far as I am aware, no such tipping points have shown up in the behavior of the biggest and most sophisticated climate models. The suggested tipping-point behavior depends on fine details that are not well resolved in the models, including details of the sea ice and the layering of the upper ocean. Also of concern are increases in the frequency and intensity of destructive weather extremes. Such increases have already been observed in recent years. Climate scientists are asking how much further the increases will go and precisely how they will develop. That question is, of course, bound up with the question of tipping points. A failure to simulate many of the extremes themselves, especially extremes of surface storminess, must count as another limitation of the climate models. The reasons are related to the resolution constraints of climate models."); Spratt D. (19 April 2023) *Faster than forecast, climate impacts trigger tipping points in the Earth system*, BULLETIN OF THE ATOMIC SCIENTISTS ("While observed warming has been close to climate model projections, the impacts have in many instances been faster and even more extreme than the models forecasted. William Ripple and his co-researchers show that many positive feedbacks are not fully accounted for in climate models…. In September 2022, Stockholm University's David Armstrong McKay and his colleagues concluded that even global warming of 1-degree Celsius risks triggering some tipping points, just one data point in an alarming mountain of research on tipping points presented in the last year and a half.... Speaking in 2018, Steffen said that the dominant linear, deterministic framework for assessing climate change is flawed, especially at higher levels of temperature rise. Model projections that don't include these feedback and cascading processes "become less useful at higher temperature levels… or, as my co-author John Schellnhuber says, we are making a big mistake when we think we can 'park' the Earth System at any given temperature rise – say 2°C – and expect it to stay there."); *and* Spratt D. & Dunlop I. (2017) *What lies beneath? The scientific understatement of climate risks*, CLIMATE CODE RED, 21 ("As discussed above, climate models are not yet good at dealing with tipping points. This is partly due to the nature of tipping points, where a particular and complex confluence of factors abruptly change a climate system characteristic and drive it to a different state. To model this, all the contributing factors and their forces have to be well identified, as well as their particular interactions, plus the interactions between tipping points. Researchers say that "complex, nonlinear systems typically shift between alternative states in an abrupt, rather than a smooth manner, which is a challenge that climate models have not yet been able to adequately meet.").

[67] Forster P., Rosen D., Lamboll R., & Rogelj J. (11 November 2022) *Guest post: What the tiny remaining 1.5C carbon budget means for climate policy*, CARBONBRIEF ("The latest estimates from the Global Carbon Project (GCP) show that total worldwide CO_2 emissions in 2022 have reached near-record levels. The GCP's estimates put the remaining carbon budget for 1.5C – specifically, the amount of CO_2 that can still be emitted for a 50% chance of staying below 1.5C of warming – at 380bn tonnes of CO_2 ($GtCO_2$). At the current rate of emissions, this budget would be blown in just nine years. While that is a disconcertingly short amount of time, the budget for 1.5C may actually be even tighter. Combining the latest insights from the Intergovernmental Panel on Climate Change (IPCC) with the GCP's data, we estimate that the remaining 1.5C carbon budget could be just 260$GtCO_2$ – around 120$GtCO_2$ smaller. If emissions continued at current levels, this budget would run out in around six and half years.").

[68] United Nations Framework Convention on Climate Change (8 September 2023) *Technical dialogue of the first global stocktake*, Synthesis report by the co-facilitators on the technical dialogue, Subsidiary Body for Scientific and Technological Advice & Subsidiary Body for Implementation, 59th Session, FCCC/SB/2023/9, 5 ("9. Key finding 4: global emissions are not in line with modelled global mitigation pathways consistent with the temperature goal of the Paris Agreement, and there is a rapidly narrowing window to raise ambition and implement existing commitments in order to limit warming to 1.5 °C above pre-industrial levels. 10. All Parties to the Paris Agreement have communicated NDCs that include mitigation targets and/or measures. A growing number of Parties have also communicated LT-LEDS. Emissions gaps are the difference between the emission levels implied by the NDCs and the average emission levels of global modelled mitigation pathways consistent with limiting warming to 1.5 °C or 2 °C. Implementation

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gaps refer to how far currently enacted policies and actions fall short of reaching stated targets. Based on current NDCs, the gap to emissions consistent with limiting warming to 1.5 °C in 2030 is estimated to be 20.3–23.9 Gt CO2 eq.2”).

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

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

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

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even when the underlying forcing changes gradually (Figure 1.1a, 1.1c). Tipping elements include, for example, the collapse of the ocean's large-scale overturning circulation in the Atlantic (Section 6.7), or the collapse of the West Antarctic Ice Sheet though a process called marine ice sheet instability (Cross-Chapter Box 8 in Chapter 3; Lenton, *et al*. 2008). Potential ocean and cryosphere tipping elements form part of the scientific case for efforts to limit climate warming to well below 2ºC (IPCC, 2018).").

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

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

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

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

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global warming below 2°C (90) (Fig. 2). Going from 1.5 to 2°C increases the likelihood of committing to WAIS and GrIS collapse near complete warm-water coral die-off, and abrupt permafrost thaw; further, the best estimate threshold for LABC [North Atlantic subpolar gyre / Labrador-Irminger Sea convection] collapse is crossed. The likelihood of triggering AMOC [Atlantic Meridional Overturning Circulation] collapse, Boreal forest shifts, and extra-polar glacier loss becomes non-negligible at >1.5°C and glacier loss becomes likely by ~2°C. A cluster of abrupt shifts occur in ESM [Earth System Models] at 1.5 to 2°C (19). Although not tipping elements, ASSI [Arctic Summer Sea Ice] loss could become regular by 2°C, gradual permafrost thaw would likely become widespread beyond 1.5°C, and land carbon sink weakening would become significant by 2°C."); *and* Intergovernmental Panel on Climate Change (2023) AR6 Synthesis Report: Climate Change 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 42 ("Risks associated with large-scale singular events or tipping points, such as ice sheet instability or ecosystem loss from tropical forests, transition to high risk between 1.5°C–2.5°C (*medium confidence*) and to very high risk between 2.5°C–4°C (*low confidence*). The response of biogeochemical cycles to anthropogenic perturbations can be abrupt at regional scales and irreversible on decadal to century time scales (*high confidence*). The probability of crossing uncertain regional thresholds increases with further warming (*high confidence*).").

[75] McIntyre M. E. (2023) *Climate tipping points: A personal view*, Physics Today 76(3): 44–49, 45–46 ("Nearly all the climate system's real complexity is outside the scope of any model, whether it's a global climate model that aims to represent the climate system as a whole or a model that only simulates the carbon cycle, ice flow, or another subsystem…. Changes taking only a few years are almost instantaneous from a climate-system perspective. They're a warning to take seriously the possibility of tipping points in the dynamics of the real climate system.[9] The warning is needed because some modelers have argued that tipping points are less probable for the real climate system than for the simplified, low-order climate models studied by dynamic-systems researchers.[3] Other researchers, however, have suggested that such a tipping point may be reached sometime in the next few decades or even sooner.[6,7] Some of its mechanisms resemble those of the Dansgaard–Oeschger warmings and would suddenly accelerate the rate of disappearance of Arctic sea ice. As far as I am aware, no such tipping points have shown up in the behavior of the biggest and most sophisticated climate models. The suggested tipping-point behavior depends on fine details that are not well resolved in the models, including details of the sea ice and the layering of the upper ocean. Also of concern are increases in the frequency and intensity of destructive weather extremes. Such increases have already been observed in recent years. Climate scientists are asking how much further the increases will go and precisely how they will develop. That question is, of course, bound up with the question of tipping points. A failure to simulate many of the extremes themselves, especially extremes of surface storminess, must count as another limitation of the climate models. The reasons are related to the resolution constraints of climate models."). *See also* Spratt D. (19 April 2023) *Faster than forecast, climate impacts trigger tipping points in the Earth system*, Bulletin of the Atomic Scientists ("While observed warming has been close to climate model projections, the impacts have in many instances been faster and even more extreme than the models forecasted. William Ripple and his co-researchers show that many positive feedbacks are not fully accounted for in climate models…. In September 2022, Stockholm University's David Armstrong McKay and his colleagues concluded that even global warming of 1-degree Celsius risks triggering some tipping points, just one data point in an alarming mountain of research on tipping points presented in the last year and a half. … Speaking in 2018, Steffen said that the dominant linear, deterministic framework for assessing climate change is flawed, especially at higher levels of temperature rise. Model projections that don't include these feedback and cascading processes "become less useful at higher temperature levels… or, as my co-author John Schellnhuber says, we are making a big mistake when we think we can 'park' the Earth System at any given temperature rise – say 2°C – and expect it to stay there."); *and* Spratt D. & Dunlop I. (2017) *What lies beneath? The scientific understatement of climate risks*, Breakthrough & The National Centre for Climate Restoration, 21 ("As discussed above, climate models are not yet good at dealing with tipping points. This is partly due to the nature of tipping points, where a particular and complex confluence of factors abruptly change a climate system characteristic and drive it to a different state. To model this, all the contributing factors and their forces have to be well identified, as well as their particular interactions, plus the interactions between tipping points. Researchers say that "complex, nonlinear systems typically shift between alternative states in an abrupt, rather than a smooth manner, which is a challenge that climate models have not yet been able to adequately meet.").

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[76] Lenton T. M., Rockstrom J., Gaffney O., Rahmstorf S., Richardson K., Steffen W., & Schellnhuber H. J. (2019) *Climate tipping points—too risky to bet against*, Comment, NATURE 575(7784): 592–595, 594 ("In our view, the clearest emergency would be if we were approaching a global cascade of tipping points that led to a new, less habitable, 'hothouse' climate state[11]. Interactions could happen through ocean and atmospheric circulation or through feedbacks that increase greenhouse-gas levels and global temperature."). *See also* Wunderling N., Donges J. F., Kurths J., & Winkelmann R. (2021) *Interacting tipping elements increase risk of climate domino effects under global warming*, EARTH SYST. DYN. 12(2): 601–619, 614 ("In this study, we show that this risk increases significantly when considering interactions between these climate tipping elements and that these interactions tend to have an overall destabilising effect. Altogether, with the exception of the Greenland Ice Sheet, interactions effectively push the critical threshold temperatures to lower warming levels, thereby reducing the overall stability of the climate system. The domino-like interactions also foster cascading, non-linear responses. Under these circumstances, our model indicates that cascades are predominantly initiated by the polar ice sheets and mediated by the AMOC. Therefore, our results also imply that the negative feedback loop connecting the Greenland Ice Sheet and the AMOC might not be able to stabilise the climate system as a whole."); Klose A. K., Wunderling N., Winkelmann R., & Donges J. F. (2021) *What do we mean, `tipping cascade'?*, ENVIRON. RES. LETT. 16(12): 125011, 1–12, 1 ("Here we illustrate how different patterns of multiple tipping dynamics emerge from a very simple coupling of two previously studied idealized tipping elements. In particular, we distinguish between a two phase cascade, a domino cascade and a joint cascade. A mitigation of an unfolding two phase cascade may be possible and common early warning indicators are sensitive to upcoming critical transitions to a certain degree. In contrast, a domino cascade may hardly be stopped once initiated and critical slowing down-based indicators fail to indicate tipping of the following element. These different potentials for intervention and anticipation across the distinct patterns of multiple tipping dynamics should be seen as a call to be more precise in future analyses of cascading dynamics arising from tipping element interactions in the Earth system."); Rocha J. C., Peterson G., Bodin Ö., & Levin S. (2018) *Cascading regime shifts within and across scales*, SCIENCE 362(6421): 1379–1383, 1383 ("A key lesson from our study is that regime shifts can be interconnected. Regime shifts should not be studied in isolation under the assumption that they are independent systems. Methods and data collection need to be further developed to account for the possibility of cascading effects. Our finding that ~45% of regime shift couplings can have structural dependence suggests that current approaches to environmental management and governance underestimate the likelihood of cascading effects."); *and* Intergovernmental Panel on Climate Change (2023) AR6 SYNTHESIS REPORT: CLIMATE CHANGE 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 16 ("Human influence has likely increased the chance of compound extreme events since the 1950s. Concurrent and repeated climate hazards have occurred in all regions, increasing impacts and risks to health, ecosystems, infrastructure, livelihoods and food (*high confidence*). Compound extreme events include increases in the frequency of concurrent heatwaves and droughts (*high confidence*); fire weather in some regions (*medium confidence*); and compound flooding in some locations (*medium confidence*). Multiple risks interact, generating new sources of vulnerability to climate hazards, and compounding overall risk (*high confidence*). Compound climate hazards can overwhelm adaptive capacity and substantially increase damage (*high confidence*).").

[77] Ritchie P. D. L., Alkhayuon H., Cox P. M., & Wieczorek S. (2023) *Rate-induced tipping in natural and human systems*, EARTH SYST. DYN. 14(3): 669–683, 669–670, 678 ("However, there is another, less obvious potential consequence of changes in external forcing. When an external forcing changes faster than some critical rate rather than necessarily by a large amount, this can lead to rate-induced tipping points (Stocker and Schmittner, 1997; Luke and Cox, 2011; Wieczorek et al., 2011; Ashwin et al., 2012; Ritchie and Sieber, 2016; Siteur et al., 2016; Suchithra et al., 2020; Arumugam et al., 2020; Pierini and Ghil, 2021; Wiec- zorek et al., 2023; Longo et al., 2021; Kuehn and Longo, 2022; Kaur and Sharathi Dutta, 2022; Hill et al., 2022; Arnscheidt and Rothman, 2022). In contrast to bifurcation-induced tipping, rate-induced tipping occurs due to fast-enough changes in external forcing and usually does not exceed any critical levels as a result of external forcing. Such tipping points are much less widely known and yet are arguably even more relevant to contemporary issues such as climate change (Lohmann and Ditlevsen, 2021; Clarke et al., 2021; O'Sullivan et al., 2022), ecosystem collapse (Scheffer et al., 2008; Vanselow et al., 2019; van der Bolt and van Nes, 2021; Neijnens et al., 2021; Vanselow et al., 2022), and the resilience of human systems (Witthaut et al., 2021)."); ("This paper highlights the importance of considering how fast external forcing is changing as opposed to solely focusing on levels of change. Consequently, the actions taken to control the rate of change in forcing are

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equally as important as the actions taken to control the level at which forcing is halted."), *discussed in* Morrison A. (14 July 2023) *Tipping Points Can Be Triggered Unexpectedly By Dangerous Rates Of Change*, UNIVERSITY OF EXETER NEWS ("Until now, critical thresholds have been assumed to be a point of no return, but the new study – published in the journal *Earth System Dynamics* – concludes that dangerous rates could trigger permanent shifts in human and natural systems before these critical levels are reached…Whilst the latest Intergovernmental Panel on Climate Change 6th Assessment Report rightly highlighted the urgency to limit global warming levels, it fell short of identifying the rate of warming as a key risk factor for climate tipping points" said joint lead author Dr Paul Ritchie, of Exeter's Global Systems Institute and the Department of Mathematics and Statistics.").

[78] Willcock S., Cooper G. S., Addy J., & Dearing J. A. (2023) *Earlier collapse of Anthropocene ecosystems driven by multiple faster and noisier drivers*, NAT SUSTAIN: 1–12, 3, 4, 5 ("In addition to earlier breakpoint dates, extra drivers can also cause ATDCs [Abrupt Threshold-Dependent Change] at levels where it would be resilient to the primary slow driver in isolation (Supplementary Section 2)"; "The addition of high noise (normalized $\sigma > 0.666$) shows that increasing the variability of the primary slow driver (in isolation) across all four models can bring forward the date of system collapse (Fig. 3). The effects outlined above are synergistic—combining multiple drivers with noise further reduces the breakpoint date beyond the effects of either multiple drivers or noise acting alone (Fig. 4)"; "Our findings also show that 1.2–14.8% of ATDCs can be triggered by additional drivers and/or noise below the threshold of driver strengths required to collapse the system if only a single driver were in effect.").

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

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this race will be impossible to finish. … 82% [o]f IPCC models do not include carbon emissions from permafrost thaw.”).

[80] Molina M., Ramanathan V., & Zaelke D. (2018) *Climate report understates threat*, Bulletin of the Atomic Scientists (“These cascading feedbacks include the loss of the Arctic’s sea ice, which could disappear entirely in summer in the next 15 years. The ice serves as a shield, reflecting heat back into the atmosphere, but is increasingly being melted into water that absorbs heat instead. Losing the ice would tremendously increase the Arctic’s warming, which is already at least twice the global average rate. This, in turn, would accelerate the collapse of permafrost, releasing its ancient stores of methane, a super climate pollutant 30 times more potent in causing warming than carbon dioxide.”).

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

[82] Schneider T., Kaul C. M., & Pressel K. G. (2019) *Possible climate transitions from breakup of stratocumulus decks under greenhouse warming*, Nat. Geosci. 12(3): 163–167, 1, 164 (“In the simulations, stratocumulus decks become unstable and break up into scattered clouds when CO_2 levels rise above 1,200 ppm. In addition to the warming from rising CO_2 levels, this instability triggers a surface warming of about 8 K globally and 10 K in the subtropics. … The subtropical SST jumps by 10 K and the tropical SST by 8 K across the stratocumulus instability (Fig. 3c,d). The tropical warming is a plausible estimate of the global-mean warming triggered by the instability. Subtropical marine stratocumulus clouds cover about 6.5% of the Earth’s surface and, where they occur, reduce the solar radiative energy flux absorbed in the climate system by ~110 $W\ m^{-2}$, compared to about a 10 $W\ m^{-2}$ reduction by scattered cumulus[22,28]. If we assume a climate sensitivity parameter of 1.2 $K\ (W\ m^{-2})^{-1}$ (as for the more sensitive among current GCMs[27]), this implies $(110 - 10)\ W\ m^{-2} \times 6.5\% \times 1.2\ K\ (W\ m^{-2})^{-1} \approx 8\ K$ global-mean surface warming when subtropical marine stratocumulus break up.”).

[83] Kemp L., Xu C., Depledge J., Ebi K. L., Gibbins G., Kohler T. A., Rockström J., Scheffer M., Schellnhuber H. J., Steffen W., & Lenton T. M. (2022) *Climate Endgame: Exploring catastrophic climate change scenarios*, Proc. Nat’l. Acad. Sci. 119(34): 1–9, 3 (“Third, climate change could exacerbate vulnerabilities and cause multiple, indirect stresses (such as economic damage, loss of land, and water and food insecurity) that coalesce into system-wide synchronous failures. This is the path of systemic risk. Global crises tend to occur through such reinforcing “synchronous failures” that spread across countries and systems, as with the 2007–2008 global financial crisis (44). It is plausible that a sudden shift in climate could trigger systems failures that unravel societies across the globe. The potential of systemic climate risk is marked: The most vulnerable states and communities will continue to be the hardest hit in a warming world, exacerbating inequities. Fig. 1 shows how projected population density intersects with

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extreme >29 °C mean annual temperature (MAT) (such temperatures are currently restricted to only 0.8% of Earth'sland surface area). Using the medium-high scenario of emissions and population growth (SSP3-7.0 emissions, and SSP3 population growth), by 2070, around 2 billion people are expected to live in these extremely hot areas. Currently, only 30 million people live in hot places, primarily in the Sahara Desert and Gulf Coast (43). Extreme temperatures combined with high humidity can negatively affect outdoor worker productivity and yields of major cereal crops. These deadly heat conditions could significantly affect populated areas in South and southwest Asia(47). Fig. 2 takes a political lens on extreme heat, overlapping SSP3-7.0 or SSP5-8.5 projections of >29 °C MAT circa 2070, with the Fragile States Index (a measurement of the instability of states). There is a striking overlap between currently vulnerable states and future areas of extreme warming. If current political fragility does not improve significantly in the coming decades, then a belt of instability with potentially serious ramifications could occur."). *See also* Stern N., Stiglitz J., & Taylor C. (2022) *The economics of immense risk, urgent action and radical change: towards new approaches to the economics of climate change*, J. ECON. METHODOL. 29(3): 181–216, 182 ("Moreover, at the core of the standard IAM methodology is an analysis of intertemporal trade-offs; how much the current generation should sacrifice in order for future generations to be spared the devastation of climate change. Rising to the climate challenges does indeed involve deep normative questions, including how different generations' welfare is to be compared and the rights of future generations. But the world has been much more focused than the IAMs on a different set of issues, the risks of catastrophic consequences. These potentially catastrophic risks are in large measure *assumed* away in the IAMs.").

[84] Pigot A. L., Merow C., Wilson A., & Trisos C. H. (2023) *Abrupt expansion of climate change risks for species globally*, NAT ECOL EVOL: 1–12, 2, 4–5 ("Third, projected thermal exposure will not occur gradually. Instead, over the coming decades, trends of increasing thermal exposure are characterized by periods of relative stability punctuated by sudden pulses, where large numbers of grid cells across a species' geographical range are exposed in a narrow window of time, with these pulses occurring at different times for different species (Fig. 1). … An abrupt expansion in the area at risk of thermal exposure is a pervasive pattern across species' geographical ranges. On average, 57% (mean ± 15% s.d.) of the exposure projected for a species this century will occur in a single decade under SSP2-4.5, with similar levels of abruptness under both higher and lower GHG emission pathways (Fig. 2a). Despite the contrasting physical environments in which species occur, the expansion of thermal exposure risks is projected to occur abruptly for both terrestrial (mean = 58% ± 16% s.d.) and marine species (mean = 51% ± 11% s.d.) across all studied organism groups, from reptiles to zooplankton, and regardless of whether species are widespread (more than a median range size of 34 grid cells; mean = 58% ± 15% s.d.) or geographically rare (fewer than 34 grid cells; mean = 56% ± 15% s.d.). … Within a species' geographical range, most grid cells have relatively narrow warming tolerances, that is, they currently experience maximum monthly temperatures close to the species' range-wide upper realized thermal limit. On average, 65% of a species' geographical range lies in the hottest half of the realized thermal niche, with 27% of the geographical range concentrated within only 10% of the thermal niche. Similar levels of warm-skewness are observed across the geographical ranges of both terrestrial and marine species (Extended Data Fig. 4). This clustering and skew in grid cell warming tolerances means that even when the climate warms gradually, multiple grid cells across a species geographical range are projected to experience thermal exposure near synchronously. … Because different GHG emission scenarios lead to similarly high rates of warming over the next two decades, thermal exposure expands abruptly (Fig. 2a) and with similar timing (Fig. 2b) irrespective of the future emission pathway (Supplementary Fig. 4). … Comparing the dynamics of exposure across all combinations of climate models and GHG emissions pathways, reveals that the number of species at risk of thermal exposure events of both high magnitude and abruptness increases rapidly with the level of global warming (Fig. 5a). For instance, at 1.5 °C of warming, 15% of species are at risk of experiencing exposure across at least 30% of their existing geographical range in a single decade, but this doubles to 30% of species at 2.5 °C of warming. This increase in risk is continuous, so that every fraction of a degree of warming that can be avoided reduces the number of species passing thermal thresholds leading to abrupt and widespread exposure. These results provide evidence that failure to achieve the Paris Agreement climate goals of limiting global warming 'well below' 2 °C, will substantially increase the risk of sudden biodiversity losses.").

[85] Intergovernmental Panel on Climate Change (2022) *Summary for Policymakers*, *in* CLIMATE CHANGE 2022: IMPACTS, ADAPTATION, AND VULNERABILITY, *Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Pörtner H.-O., Roberts D. C., Tignor M., Poloczanska E. S., Mintenbeck K., Alegría A., Craig M., Langsdorf S., Löschke S., Möller V., Okem A., & Rama B. (eds.), SPM-19–20

("SPM.B.6 If global warming transiently exceeds 1.5°C in the coming decades or later (overshoot)[37], then many human and natural systems will face additional severe risks, compared to remaining below 1.5°C (*high confidence*). Depending on the magnitude and duration of overshoot, some impacts will cause release of additional greenhouse gases (*medium confidence*) and some will be irreversible, even if global warming is reduced (*high confidence*). (Figure SPM.3) … SPM.B.6.1 While model-based assessments of the impacts of overshoot pathways are limited, observations and current understanding of processes permit assessment of impacts from overshoot. Additional warming, e.g., above 1.5°C during an overshoot period this century, will result in irreversible impacts on certain ecosystems with low resilience, such as polar, mountain, and coastal ecosystems, impacted by ice-sheet, glacier melt, or by accelerating and higher committed sea level rise (*high confidence*).[38] Risks to human systems will increase, including those to infrastructure, low-lying coastal settlements, some ecosystem-based adaptation measures, and associated livelihoods (*high confidence*), cultural and spiritual values (*medium confidence*). Projected impacts are less severe with shorter duration and lower levels of overshoot (*medium confidence*). … SPM.B.6.2 Risk of severe impacts increase with every additional increment of global warming during overshoot (*high confidence*). In high-carbon ecosystems (currently storing 3,000 to 4,000 GtC)[39] such impacts are already observed and are projected to increase with every additional increment of global warming, such as increased wildfires, mass mortality of trees, drying of peatlands, and thawing of permafrost, weakening natural land carbon sinks and increasing releases of greenhouse gases (*medium confidence*). The resulting contribution to a potential amplification of global warming indicates that a return to a given global warming level or below would be more challenging (*medium confidence*).").

[86] National Snow & Ice Data Center (15 September 2022) *Arctic Weather and Climate* ("Changes in the Arctic climate are important because the Arctic acts as a refrigerator for the rest of the world—it helps cool the planet. So changes in the Arctic climate could affect the climate in the rest of the world. Changes in the Arctic have effects that cascade through the food chain… Researchers say that the changes in the Arctic are worrisome, because they could lead to feedback effects that lead to further warming. For instance, when the white sea ice melts in summer, areas of dark open water are exposed which can absorb more heat from the sun. That extra heat then helps melt even more ice. The loss of sea ice is known to be one of the drivers of Arctic amplification. Permafrost may also be involved in feedbacks. As permafrost thaws, plants and animals that were frozen in the ground begin to decay. When they decay, they release carbon dioxide and methane back to the atmosphere that can contribute to further warming. The changing vegetation of the Arctic also affects the brightness of the surface, which then influences warming. As the Arctic atmosphere warms, it can hold more water vapor, which is an important greenhouse gas."). *See also* Jansen E., *et al.* (2020) *Past perspectives on the present era of abrupt Arctic climate change*, NAT. CLIM. CHANGE 10: 714–721, 714 ("Annual mean temperature trends over the Arctic during the past 40 years show that over this period, where satellite data are available, major portions have warmed by more than 1 °C per decade (Fig. 1a, red colours and outlined portion; a warming of 4 °C within 40 years is hereafter referred to as 1 °C per decade). … Using a criterion based on the speed of near-surface air temperature warming over the past four decades, we find that the current Arctic is experiencing rates of warming comparable to abrupt changes, or D–O events, recorded in Greenland ice cores during the last glacial period. [During the last glacial period (120,000–11,000 years ago), more than 20 abrupt periods of warming, known as Dansgaard–Oeschger (D–O) events, took place[18,19].] Both past changes in the Greenland ice cores and the ongoing trends in the Arctic are directly linked to sea-ice retreat—in the Nordic Seas during glacial times and in the Eurasian Arctic at present. Abrupt changes have already been experienced and could, according to state-of-the-art climate models, occur in the Arctic during the twenty-first century, but climate models underestimate current rates of change in this region.").

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

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

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warming in the polar regions was much larger than in the tropics, due in part to the albedo decrease from shrinking snow/ice area.”).

[89] Sumata H., de Steur L., Divine D. V., Granskog M. A., & Gerland S. (2023) *Regime shift in Arctic Ocean sea ice thickness*, NATURE, 615(7952): 443–49, 448 (“Thus, summer ice extent and thickness in areas of ice formation has not recovered to the state before 2007 (Fig. 4c). In addition, continuing weakening of the cold halocline in the Siberian sector also influenced the upper ocean heat content46 and possibly slowed down ice growth offshore of the Laptev Sea in recent years. Our analysis demonstrates the long-lasting impact of climate change on Arctic sea ice through reduced residence time, suggesting an irreversible response of Arctic sea ice thickness connected to an increase of ocean heat content in areas of ice formation.”), *discussed in* Dance S. (16 March 2023) *Arctic ice has seen an ‘irreversible’ thinning since 2007, study says*, WASHINGTON POST (“The study’s authors said that would take a long time even under the most optimistic global warming and emissions reduction scenarios. Even if carbon dioxide emissions fell to zero sometime in the next 50 years, it would take decades more for the ocean to lose all the heat it has accumulated since humans began burning fossil fuels and emitting greenhouse gases.”).

[90] Rantanen M., Karpechko A. Y., Lipponen A., Nordling K., Hyvärinen O., Ruosteenoja K., Vihma T. & Laaksonen A. (2022) *The Arctic has warmed nearly four times faster than the globe since 1979*, COMMUN. EARTH ENVIRON. 3(168): 1–10, 3 (“During 1979–2021, major portions of the Arctic Ocean were warming at least four times as fast as the global average (Fig. 1c). The most extreme AA values occur in the sea areas near Novaya Zemlya, which were locally warming up to seven times as fast as the global average. These high warming rates are consistent with recent research[44], and evidently, the primary reason for such a high amplification ratio is the reduction of cold-season ice cover, which has been most pronounced in the Barents Sea[44,45]. Furthermore, it has been found that changes in atmospheric circulation have amplified the warming in this area[46,47]. In general, there are no regions within the Arctic Circle where AA[43] is smaller than two, apart from the northern North Atlantic.”), *discussed in* Budryk Z. (11 August 2022) *Arctic warming up to four times as fast as global average: study*, THE HILL; *and* Fountain H. (11 August 2022) *Arctic Warming Is Happening Faster Than Described, Analysis Shows*, THE NEW YORK TIMES. *See also* Jacobs P., Lenssen N. J. L., Schmidt G. A., & Rohde R. A. (2021) *The Arctic Is Now Warming Four Times As Fast As the Rest of the Globe*, Presentation at the American Geophysical Union Fall Meeting, A13E-02 (“We demonstrate the Arctic is likely warming over 4 times faster than the rest of the world, some 3-4 times the global average, with higher rates found both for more recent intervals as well as more accurate latitudinal boundaries. These results stand in contrast to the widely-held conventional wisdom — prevalent across scientific and lay publications alike — that the Arctic is "only" warming around twice as fast as the global mean.”), *discussed in* Voosen P. (14 December 2021) *The Arctic is warming four times faster than the rest of the world*, SCIENCE.

[91] National Oceanic and Atmospheric Administration (13 December 2022) *Human-caused climate change fuels warmer, wetter, stormier Arctic* (“Arctic **annual air temperatures** from October 2021 to September 2022 were the sixth warmest dating back to 1900, continuing a decades-long trend in which Arctic air temperatures have warmed faster than the global average. The Arctic's seven warmest years since 1900 have been the last seven years.”).

[92] Arctic Monitoring and Assessment Programme (2021) ARCTIC CLIMATE CHANGE UPDATE 2021: KEY TRENDS AND IMPACTS, Summary for Policymakers, 6 (“The extent of Arctic sea ice in September declined by 43% between 1979 and 2019, and—with the exception of the Bering Sea—sea-ice extent and area are declining throughout the Arctic in all months. Sea-ice cover also continues to be younger and thinner than during the 1980s, 1990s, and early 2000s.”). *See also* Druckenmiller M. L., *et al.* (2021) *The Arctic*, BULL. AM. MET. SOC. 102(8): S263–S316, S280 (“September is the month when the minimum annual sea ice extent occurs. In 2020, this average monthly ice extent was 3.92 million km^2 (Fig. 5.8b), the second lowest monthly extent in the 42-year satellite record. On 15 September, the annual minimum Arctic sea ice extent of 3.74 million km^2 was reached; this was also the second lowest on record. The September monthly extent has been decreasing at an average rate of −82,700 km^2 per year since 1979 (−13.1% per decade relative to the 1981–2010 average; Fig. 5.8c).”).

[93] Kim Y.-H., Min S.-K., Gillett N. P., Notz D., & Malinina E. (2023) *Observationally-constrained projections of an ice-free Arctic even under a low emission scenario*, NAT. COMMUN. 14(3139): 1–8, 5 (“Based on the GHG+ scaling factors, we produce observationally-constrained future changes in Arctic SIA under four SSP scenarios. Results

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indicate that the first sea ice-free September will occur as early as the 2030s–2050s irrespective of emission scenarios. Extended occurrences of an ice-free Arctic in the early summer months are projected later in the century under higher emissions scenarios.”). *See also* Bonan D. B., Schneider T., Eisenman I., & Wills R. C. J. (2021) *Constraining the Date of a Seasonally Ice-Free Arctic Using a Simple Model*, Geophys. Res. Lett. 48(18): 1–12, 1 (“Under a high-emissions scenario, an ice-free Arctic will likely (>66% probability) occur between 2036 and 2056 in September and between 2050 and 2068 from July to October. Under a medium-emissions scenario, the “likely” date occurs between 2040 and 2062 in September and much later in the 21st century from July to October.”); Docquier D. & Koenigk T. (2021) *Observation-based selection of climate models projects Arctic ice-free summers around 2035*, Commun. Earth Environ. 2(144): 1–8, 4, 6 (“In the high-emission scenario, five out of six selection criteria that include ocean heat transport provide a first ice-free Arctic in September before 2040 (range of multi-model means: 2032–2039), more than 20 years before the date of ice-free Arctic for the multi-model mean without model selection (i.e. 2061)”; “This model selection reveals that sea-ice area and volume reach lower values at the end of this century compared to the multi-model mean without selection. This arises both from a more rapid reduction in these quantities through this century and from a lower present-day sea-ice area. Using such a model selection, the timing of an almost ice-free Arctic in summer is advanced by up to 29 years in the high-emission scenario, i.e. it could occur as early as around 2035.”); Peng G., Matthews J. L., Wang M., Vose R., & Sun L. (2020) *What Do Global Climate Models Tell Us about Future Arctic Sea Ice Coverage Changes?*, Climate 8(15): 1–24, 17 (“Excluding the values later than 2100, the averaged projected [first ice-free Arctic summer year (FIASY)] value for RCP4.5 was 2054 with a spread of 74 years; for RCP8.5, the averaged FIASY was 2042 with a spread of 42 years. ...which put the mean FIASY at 2037. The RCP8.5 projections tended to push FIASY earlier, except for those of the MICRO-ESM and MICRO-ESM-CHEM models. Those two models also tended to project earlier Arctic ice-free dates and longer durations.”); *and* Overland J. E. & Wang M. (2013) *When will the summer Arctic be nearly sea ice free?*, Geophys. Res. Lett. 40(10): 2097–2101, 2097 (“Three recent approaches to predictions in the scientific literature are as follows: (1) extrapolation of sea ice volume data, (2) assuming several more rapid loss events such as 2007 and 2012, and (3) climate model projections. Time horizons for a nearly sea 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.”). However, findings of ice-free September Arctic sea ice may be too early by a decade if models are not properly accounting for larger changes in atmospheric circulation, *according to* Topál D. & Ding Q. (2023) *Atmospheric circulation-constrained model sensitivity recalibrates Arctic climate projections*, Nat. Clim. Chang. 1–9, 5 (“To showcase our point, we use the abovementioned method to constrain the timing of the first sea-ice-free September in the SMILEs and CMIP6 models. The cumulative probability density functions (CDFs) corresponding to the time of emergence of the first seasonally sea-ice-free Arctic[52,5]3 (below 1 million km^2 in September) in the raw and the calibrated SIE time series in the model ensembles show prospects of a 9–11-year delay of the ‘likely’ (in IPCC[54] terms) probability ($P > 0.66$) of a September ice-free Arctic, such that an ice-free summer before 2050 is ‘as likely as not’ (in IPCC terms $0.33 < P < 0.66$) (Fig. 5c; Methods). This result is in contrast to estimates from previous studies that project ice-free September as early as mid-century[33]. Our results are also at odds with a recent study, where the authors used Arctic temperatures as an emergent constraint on ice-free projections in CMIP6 (ref. 40).”).

[94] Bonan D. B., Schneider T., Eisenman I., & Wills R. C. J. (2021) *Constraining the Date of a Seasonally Ice-Free Arctic Using a Simple Model*, Geophys. Res. Lett. 48(18): 1–12, 1 (“Under a high-emissions scenario, an ice-free Arctic will likely (>66% probability) occur between 2036 and 2056 in September and between 2050 and 2068 from July to October. Under a medium-emissions scenario, the “likely” date occurs between 2040 and 2062 in September and much later in the 21st century from July to October.”). However, findings of ice-free September Arctic sea ice may be too early by a decade if models are not properly accounting for larger changes in atmospheric circulation, *according to* Topál D. & Ding Q. (2023) *Atmospheric circulation-constrained model sensitivity recalibrates Arctic climate projections*, Nat. Clim. Chang. 1–9, 5 (“To showcase our point, we use the abovementioned method to constrain the timing of the first sea-ice-free September in the SMILEs and CMIP6 models. The cumulative probability density functions (CDFs) corresponding to the time of emergence of the first seasonally sea-ice-free Arctic[52,5]3 (below 1 million km^2 in September) in the raw and the calibrated SIE time series in the model ensembles show prospects of

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a 9–11-year delay of the ‘likely’ (in IPCC[54] terms) probability ($P > 0.66$) of a September ice-free Arctic, such that an ice-free summer before 2050 is ‘as likely as not’ (in IPCC terms $0.33 < P < 0.66$) (Fig. 5c; Methods). This result is in contrast to estimates from previous studies that project ice-free September as early as mid-century[33]. Our results are also at odds with a recent study, where the authors used Arctic temperatures as an emergent constraint on ice-free projections in CMIP6 (ref. 40).”).

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

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

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

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

[99] Zhang J., Lindsay R., Schweiger A., & Steele M. (2013) *The impact of an intense summer cyclone on 2012 Arctic sea ice retreat*, Geophys. Res. Lett. 40(4): 720–726, 722 (“The rapid reduction in ice volume during the storm is due to enhanced ice melt (Figures 3a–3d). The simulated total ice melt is 0.12×10^3 km^3 d^{-1} before the cyclone, but almost doubled during the cyclone, averaging 0.21×10^3 km^3 d^{-1} (or 0.17×10^3 km^3 d^{-1} in the ICAPS) during 6–8 August (Figure 2c and Table 1). The enhanced melt is widespread in the ICAPS, but is strongest in the Canada Basin, where ice melt is as high as 0.12 m d^{-1} (Figures 3b and 3c). This explains the large decrease in ice thickness during the storm in these areas (Figures 1j–1l), up to 0.5 m by 10 August (Figure 1l). The simulated ice in most of these areas was already thin on 4 August before the storm (Figures 1i and 2b).”). *See also* Valkonen E., Cassano J., & Cassano E. (2021) *Arctic Cyclones and their Interactions With the Declining Sea Ice: A Recent Climatology*, J. Geophys. Res. Atmos. 126(12): 1–35, 20–21 (“We also showed that the increased cyclone counts in the cold season were indeed connected to the declining sea ice in both the warm and cold seasons (Figures 11and A15). Less sea ice in the cold

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season or the following warm season was related to increased cyclone counts in the cold season."); Finocchio P. M. & Doyle J. D. (2022) *Summer Cyclones and Their Association With Short-Term Sea Ice Variability in the Pacific Sector of the Arctic*, Front. Earth Sci. 9(738497): 1–17, 15 ("The advective tendency of SIC due to the 10-m wind is one of the most consistent predictors of both local and regional ice loss for the large sample of cyclones in the ECB region. We find the strongest relationship between advection and sea ice loss for low concentration sea ice in August. This supports previous studies arguing that the reduced mechanical strength of lower concentration sea ice makes it more susceptible to wind-induced drift and deformation (Hakkinen et al., 2008; Rampal et al., 2009; Spreen et al., 2011)."); *and* Finocchio P. M., Doyle J. D., & Stern D. P. (2022) *Accelerated Sea Ice Loss from Late Summer Cyclones in the New Arctic*, J. Clim. 35(23): 4151–4169, 4151 ("We compare the 1–7-day changes in sea ice area and thickness following days in each month with and without cyclones from two decades: 1991–2000 and 2009–18. Only in August do cyclones locally accelerate seasonal sea ice loss on average, and the ability of August cyclones to accelerate ice loss has become more pronounced in the recent decade. The recent increase in ice loss following August cyclones is most evident in the Amerasian Arctic (140°E–120°W), where reanalyses indicate that the average upper-ocean temperature has increased by 0.2°–0.8°C and the average ice thickness has decreased by almost 1 m between the two decades. Such changes promote cyclone-induced ocean mixing and sea ice divergence that locally increase the likelihood for rapid ice loss near cyclones. In contrast, June cyclones in both decades locally slow down seasonal sea ice loss. Moreover, the 7-day sea ice loss in June has increased from the early to the recent decade by 67% more in the absence of cyclones than in the presence of cyclones. The largest increases in June ice loss occur in the Eurasian Arctic (0°–140°E), where substantial reductions in average surface albedo in the recent decade have allowed more of the abundant insolation in the absence of cyclones to be absorbed at the sea surface."). Research is also underway that analyzes 2022 trends for accelerated ice loss in the Arctic due to late summer cyclones: *see* Hand E. (23 August 2022) *Arctic stormchasers brave giant cyclones to understand how they chew up sea ice*, Science.

[100] Rantanen M., Karpechko A. Y., Lipponen A., Nordling K., Hyvärinen O., Ruosteenoja K., Vihma T. & Laaksonen A. (2022) *The Arctic has warmed nearly four times faster than the globe since 1979*, Commun. Earth Environ. 3(168): 1–10, 3 ("During 1979–2021, major portions of the Arctic Ocean were warming at least four times as fast as the global average (Fig. 1c). The most extreme AA values occur in the sea areas near Novaya Zemlya, which were locally warming up to seven times as fast as the global average. These high warming rates are consistent with recent research[44], and evidently, the primary reason for such a high amplification ratio is the reduction of cold-season ice cover, which has been most pronounced in the Barents Sea[44,45]. Furthermore, it has been found that changes in atmospheric circulation have amplified the warming in this area[46,47]. In general, there are no regions within the Arctic Circle where AA[43] is smaller than two, apart from the northern North Atlantic."), *discussed in* Budryk Z. (11 August 2022) *Arctic warming up to four times as fast as global average: study*, The Hill; *and* Fountain H. (11 August 2022) *Arctic Warming Is Happening Faster Than Described, Analysis Shows*, The New York Times. *See also* Jacobs P., Lenssen N. J. L., Schmidt G. A., & Rohde R. A. (2021) *The Arctic Is Now Warming Four Times As Fast As the Rest of the Globe*, Presentation at the American Geophysical Union Fall Meeting, A13E-02 ("We demonstrate the Arctic is likely warming over 4 times faster than the rest of the world, some 3-4 times the global average, with higher rates found both for more recent intervals as well as more accurate latitudinal boundaries. These results stand in contrast to the widely-held conventional wisdom — prevalent across scientific and lay publications alike — that the Arctic is "only" warming around twice as fast as the global mean."), *discussed in* Voosen P. (14 December 2021) *The Arctic is warming four times faster than the rest of the world*, Science; *and* Chylek P., Folland C., Klett J. D., Wang M., Hengartner N., Lesins G., & Dubey M. K. (2022) *Annual Mean Arctic Amplification 1970–2020: Observed and Simulated by CMIP6 Climate Models*, Geophys. Res. Lett. 49(13): 1–8, 1 ("While the annual mean Arctic Amplification (AA) index varied between two and three during the 1970–2000 period, it reached values exceeding four during the first two decades of the 21st century. The AA did not change in a continuous fashion but rather in two sharp increases around 1986 and 1999. During those steps the mean global surface air temperature trend remained almost constant, while the Arctic trend increased. Although the "best" CMIP6 models reproduce the increasing trend of the AA in 1980s they do not capture the sharply increasing trend of the AA after 1999 including its rapid step-like increase. We propose that the first sharp AA increase around 1986 is due to external forcing, while the second step close to 1999 is due to internal climate variability, which models cannot reproduce in the observed time…. Annual mean Arctic Amplification (AA) within the period 1970–2020 changed in steep steps around 1986 and 1999. It reached values over 4.0…"), *discussed in* Los Alamos National Laboratory (5 July 2022) *Arctic temperatures are increasing four times faster than global warming*, Phys.org.

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

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

[103] Ciavarella A., *et al.* (2021) *Prolonged Siberian heat of 2020 almost impossible without human influence*, CLIM. CHANGE 166(9): 1–18, 1 ("Over the first half of 2020, Siberia experienced the warmest period from January to June since records began and on the 20th of June the weather station at Verkhoyansk reported 38 °C, the highest daily maximum temperature recorded north of the Arctic Circle… We show that human-induced climate change has dramatically increased the probability of occurrence and magnitude of extremes in both of these (with lower confidence for the probability for Verkhoyansk) and that without human influence the temperatures widely experienced in Siberia in the first half of 2020 would have been practically impossible."). *See also* DeGeorge K. (24 June 2021) *Siberia is seeing record heat — again*, ARCTICTODAY ("On Monday, satellites with the European Union's Copernicus Earth observation program detected exceptionally high ground temperatures across much of the region, with a high reaching an astounding 48 degrees Celsius (118 degrees Fahrenheit) near Verkhoyansk, in the Sakha Republic, while other sites recorded highs of 43 degrees C (109.4 degrees F) and 37 degrees C (98.6 degrees F). It's important to note that those are ground temperatures, not air temperatures. For example, that latter figure was recorded in Saskylakh, also in the Sakha Republic, where air temperatures taken at the same time were a slightly cooler 31.9 degrees C (89.4 degrees F). That still set a record for Saskylakh, though, as the hottest pre-solstice temperature recorded there since measurements began in 1936. The news comes a month after the Arctic Council's Arctic Monitoring and Assessment working group issued a report confirming that the region is now warming three times faster than the global average, rather than twice as fast. And it comes almost exactly a year after the first 100-degree (Fahrenheit) temperature was recorded north of the Arctic Circle — also in Verkhoyansk.").

[104] Schweiger A. J., Steele M., Zhang J., Moore G. W. K., & Laidre K. L. (2021) *Accelerated sea ice loss in the Wandel Sea points to a change in the Arctic's Last Ice Area*, COMMUN. EARTH ENVIRON. 2(122): 1–11, 2, 5–6 ("The Polarstern's route was guided by satellite images showing extensive areas of open water and sea ice concentration (SIC) as low as 70% at 87N (Figs. 1a, S1b). We define our WS study area by 81.5°N–85°N, 10°W–50°W, the same area where we saw signs of change in February 201810. Daily 2020 WS SIC drops below the 5th percentile of the 1979–2020 time series on July 25 and stays there almost until the end of August (Fig. 1b). August 14, 2020 constitutes a record low 52% SIC minimum (Fig. 1c). Several earlier years (e.g., 1985: 57%, 1990: 67%, and 1991: 62%) also show significant low SIC minima, although none as low as 2020."). *See also* page 1 ("During spring 2020, ice accumulated in the WS (Fig. 4a, b) in response to anomalous advection (mostly in February; Fig. 4c, d). As a result, ice thickness was near its 1979–2020 mean value by June 1 according to PIOMAS; Fig. 2c), and actually thicker than in recent years (2011–2019) as confirmed by the combined CryoSat-2/SMOS satellite product… While primarily driven by unusual weather, climate change in the form of thinning sea ice contributed significantly to the record low August 2020 SIC in the WS. Several advection events, some relatively early in the melt season, transported sea ice out of the region and allowed the accumulation of heat from the absorption of solar radiation in the ocean. This heat was mixed upward and contributed to rapid melt during high wind events, notably between August 9 and 16. Ocean-forced melting in this area that is traditionally covered by thick, compact ice is a key finding of this study. … These ensemble experiments underline the importance of both spring sea ice and summer atmospheric forcing to August

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SIC. In summary, we find that: Spring ice conditions were mostly responsible for the summer SIC anomaly through the end of July, while the atmosphere was mainly responsible for driving SIC to a record low during August. Partitioning the impact of 2020 spring initial sea ice conditions vs. summer atmospheric forcing on the sea ice anomaly at the time of the WS sea ice minimum on August 14 (see "Methods") attributes ~20% to the initial conditions while ~80% is the due to the atmospheric forcing.").

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

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

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

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

[109] Arctic Monitoring and Assessment Programme (2021) Arctic Climate Change Update 2021: *Key Trends and Impacts, Summary for Policy-Makers*, 6 ("The extent of Arctic sea ice in September declined by 43% between 1979 and 2019, and—with the exception of the Bering Sea—sea-ice extent and area are declining throughout the Arctic in all months. Sea-ice cover also continues to be younger and thinner than during the 1980s, 1990s, and early 2000s."). *See also* Druckenmiller M. L., *et al.* (2021) *The Arctic*, Bull. Am. Met. Soc. 102(8): S263–S316, S280 ("September is the month when the minimum annual sea ice extent occurs. In 2020, this average monthly ice extent was 3.92 million km^2 (Fig. 5.8b), the second lowest monthly extent in the 42-year satellite record. On 15 September, the annual minimum Arctic sea ice extent of 3.74 million km^2 was reached; this was also the second lowest on record. The September monthly extent has been decreasing at an average rate of −82,700 km^2 per year since 1979 (−13.1% per decade relative to the 1981–2010 average; Fig. 5.8c).").

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[110] Docquier D. & Koenigk T. (2021) *Observation-based selection of climate models projects Arctic ice-free summers around 2035*, Commun. Earth Environ. 2(144): 1–8, 4, 6 ("In the high-emission scenario, five out of six selection criteria that include ocean heat transport provide a first ice-free Arctic in September before 2040 (range of multi-model means: 2032–2039), more than 20 years before the date of ice-free Arctic for the multi-model mean without model selection (i.e. 2061) … This model selection reveals that sea-ice area and volume reach lower values at the end of this century compared to the multi-model mean without selection. This arises both from a more rapid reduction in these quantities through this century and from a lower present-day sea-ice area. Using such a model selection, the timing of an almost ice-free Arctic in summer is advanced by up to 29 years in the high-emission scenario, i.e. it could occur as early as around 2035."). *See also* Peng G., Matthews J. L., Wang M., Vose R., & Sun L. (2020) *What Do Global Climate Models Tell Us about Future Arctic Sea Ice Coverage Changes?*, Climate 8(15): 1–24, 17 ("Excluding the values later than 2100, the averaged projected [first ice-free Arctic summer year (FIASY)] value for RCP4.5 was 2054 with a spread of 74 years; for RCP8.5, the averaged FIASY was 2042 with a spread of 42 years. … which put the mean FIASY at 2037. The RCP8.5 projections tended to push FIASY earlier, except for those of the MICRO-ESM and MICRO-ESM-CHEM models. Those two models also tended to project earlier Arctic ice-free dates and longer durations."); *and* Overland J. E. & Wang M. (2013) *When will the summer Arctic be nearly sea ice free?*, Geophys. Res. Lett. 40(10): 2097–2101, 2097 ("Three recent approaches to predictions in the scientific literature are as follows: (1) extrapolation of sea ice volume data, (2) assuming several more rapid loss events such as 2007 and 2012, and (3) climate model projections. Time horizons for a nearly sea 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.").

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

[112] National Aeronautics and Space Administration, *Arctic Sea Ice Minimum Extent* (*last visited* 3 September 2023) ("Arctic sea ice reaches its minimum extent (the area in which satellite sensors show individual pixels to be at least 15% covered in ice) each September. September Arctic sea ice is now shrinking at a rate of 12.6% per decade, compared to its average extent during the period from 1981 to 2010.").

[113] Wang X., Liu Y., Key J. R., & Dworak R. (2022) *A New Perspective on Four Decades of Changes in Arctic Sea Ice from Satellite Observations*, Remote Sens. 14(8): 1846, 1–22, 19–20 ("Arctic AICA SIE was reduced 22% over the last four decades, mainly caused by PICA SIE reduction that declined at an annual rate of −1.105 × 105 km2 per year. The annual increase in SICA SIE, at a rate of 2.640 × 104 km2 per year, does not offset the decline in the PICA SIE, resulting in a net loss of AICA SIE at a rate of −7.871 × 104 km2 per year. The AICA SIE in September had a minimum extent of 4.32892 × 106 km2 in 2020 compared to the much larger SIE of 7.63860 × 106 km2 in 1982, resulting in a 43% decline over the past four decades.").

[114] Wang X., Liu Y., Key J. R., & Dworak R. (2022) *A New Perspective on Four Decades of Changes in Arctic Sea Ice from Satellite Observations*, Remote Sens. 14(8): 1846, 1–22, 13 ("The AICA SIT in March decreased to 1.80 m in 2020 from 3.85 m in 1982, resulting in a 53% decrease at a rate of −0.058 m per year when Arctic sea ice reaches its seasonal maximum extent in the Arctic Ocean. In September, when the Arctic sea ice is at its minimum extent, AICA SIT declined to 0.71 m in 2020 from 1.36 m in 1982, resulting in a 48% decrease at a rate of −0.016 m per year. On an annual average, AICA SIT decreased by 1.22 m, which is 52% of the 2.35 m in 1982, resulting in 1.13 m in 2020. Both PICA and SICA SIT declined to 1.32 m and 0.96 m in 2020 from 2.55 m and 1.86 m in 1982, respectively. All of the Arctic SIT trends in all months are statistically significant, however the SICA SIT trend in September is

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slightly positive, with a confidence level of 0.496 due to the very small sample size of seasonal ice in September (Table 3).”).

[115] Wang X., Liu Y., Key J. R., & Dworak R. (2022) *A New Perspective on Four Decades of Changes in Arctic Sea Ice from Satellite Observations*, Remote Sens. 14(8): 1846, 1–22, 18 (“Over 1982–2020, AICA SIV decreased to 20,679.0 km3 in 2020 from 51,216.6 km3 in 1982, resulting in a 60% decrease at a rate of −859.2 km3 per year in March. In September, AICA SIV declined to 2462.0 km3 in 2020 from 8931.2 km3 in 1982, resulting in a 72% decrease at a rate of −170.2 km3 per year. Based on an annual average, AICA SIV decreased by 17,284.8 km3, which is 63% of the 27,590.4 km3 in 1982, resulting in 10,305.5 km3 SIV in 2020. PICA SIV and SICA SIV declined to 5766.0 km3 and 4522.8 km3 in 2020 from 20,313.0 km3 and 7271.0 km3 in 1982, respectively. In addition, the ratios of PICA SIV and SICA SIV to AICA SIV were declining in March, when Arctic sea ice reaches its maximum volume over 1982–2020 (Figure 14). It is around 2019 when the SICA SIV proportion started surpassing the PICA SIV proportion in March.”).

[116] National Snow and Ice Data Center (21 September 2020) *Arctic sea ice decline stalls out at second lowest minimum* (“On September 15, Arctic sea ice likely reached its annual minimum extent of 3.74 million square kilometers (1.44 million square miles). The minimum ice extent is the second lowest in the 42-year-old satellite record, reinforcing the long-term downward trend in Arctic ice extent. Sea ice extent will now begin its seasonal increase through autumn and winter. …*Please note that this is a preliminary announcement. Changing winds or late-season melt could still reduce the Arctic ice extent, as happened in 2005 and 2010. NSIDC scientists will release a full analysis of the Arctic melt season, and discuss the Antarctic winter sea ice growth, in early October*. … The 14 lowest extents in the satellite era have all occurred in the last 14 years.”). *See also* Richter-Menge J., Druckenmiller M. L. & Thoman R. L. (2020) *15 Years of Arctic Observation: A Retrospective*, *in* Arctic Report Card 2020, Thoman R. L., Richter-Menge J., & Druckenmiller M. L. (eds.), National Oceanic and Atmospheric Administration, 8 (“As it turns out, the first publication in 2006 coincided with a cusp of transformation in the sea ice cover, which is literally and figuratively central to the Arctic system. The 2007 September minimum sea ice extent stunned scientists and grabbed world-wide media attention with a new record minimum that was 23% below the previous record low set in 2005. Just five years later, in 2012, the 2007 record was overtaken by a September minimum sea ice extent that was 18% below 2007. The 2012 record low still stands as of 2020. However, in the 14 years since ARC2006 the late summer sea ice minimum extent has never returned to pre-2007 values.”).

[117] National Snow and Ice Data Center (20 September 2022) *The sun sets on the melt season* (“As of September 19, 2022, Arctic sea ice extent stood at 4.68 million square kilometers (1.81 million square miles), placing it ninth lowest in the satellite record for the date. Between September 1 and September 19, the Arctic lost a total of 522,000 square kilometers (202,000 square miles) of ice, at an average rate of 27,500 square kilometers (10,600 square miles) per day. This was slightly faster than the average daily loss rate over this period. As of September 19, sea ice extent was tracking close to the levels observed in 2010, and the spatial pattern of sea ice extent is similar.”). *See also* National Snow and Ice Data Center (22 September 2021) *Arctic Sea Ice at Highest Minimum Since 2014* (“On September 16, Arctic sea ice likely reached its annual minimum extent of 4.72 million square kilometers (1.82 million square miles). The 2021 minimum is the twelfth lowest in the nearly 43-year satellite record. The last 15 years are the lowest 15 sea ice extents in the satellite record. The amount of multi-year ice (ice that has survived at least one summer melt season), is one of the lowest levels in the ice age record, which began in 1984.”).

[118] Perovich D., *et al.* (2020) *Sea Ice*, *in* Arctic Report Card 2020, Thoman R. L., Richter-Menge J., & Druckenmiller M. L. (eds.), National Oceanic and Atmospheric Administration, 29–30, 48 (“The oldest ice (>4 years old), which once dominated within the Arctic Ocean, now makes up just a small fraction of the Arctic Ocean ice pack in March, when the sea ice cover is at its maximum extent (Fig. 3). In 1985, 33% of the ice pack was very old ice (>4 years), but by March 2019 old ice only constituted 1.2% of the ice pack within the Arctic Ocean. The total extent of the oldest ice declined from 2.52 million km^2 in March 1985 to 0.09 million km^2 in March 2019. … First-year ice now dominates the sea ice cover, comprising ~70% of the March 2019 ice pack, compared to approximately 35–50% in the 1980s. Given that older ice tends to be thicker, the sea ice cover has transformed from a strong, thick ice mass in the 1980s to a younger, more fragile, and thinner ice mass in recent years. First-year ice is therefore more vulnerable to melting out in summer, thereby increasing the likelihood of lower minimum ice extents. … The oldest ice (> 4 years

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old) was once a major component of the Arctic sea ice cover, but now makes up just a small fraction of the March Arctic Ocean ice pack (Fig. 3). In 1985, 33% of the ice pack was very old ice (> 4 years), but by March 2020 old ice only constituted 4.4% of the ice pack within the Arctic Ocean. The total extent of the oldest ice declined from 2.70 million km^2 in March 1985 to 0.34 million km^2 in March 2020. The March 2020 extent of > 4 year old ice increased from the record-low year in 2019 when it was only 1.2% (0.09 million km^2) of the ice cover. This increase was due to 3–4 year old ice surviving a year and aging into > 4 year old ice. The 3–4 year old cover dropped from 6.4% in 2019 to 3.7% in 2020. Overall the percentage of ice 3 years and older was effectively unchanged. Note that these percentages are relative to ice in the Arctic Ocean region (Fig. 3, bottom inset); areas in the peripheral seas outside of this region have little or no older ice and thus do not show any change over time."). *See also* Druckenmiller M. L., *et al.* (2021) *The Arctic*, BULL. AM. MET. SOC. 102(8): S263–S316, S282 ("The dominant ice type is now first-year ice (0–1 years old), which comprised about 70% of the March 2020 Arctic Ocean ice cover. The median ice age dropped from 2–3 years old in the mid-1980s to less than 1 year old by 2020. The total extent of the oldest ice (>4 years old) declined from 2.50 million km^2 in March 1985 to 0.34 million km^2 in March 2020."); World Meteorological Organization (2020) UNITED IN SCIENCE 2020, 9 ("Arctic (as well as sub-Arctic) sea ice has seen a long-term decline in all months during the satellite era (1979–present), with the largest relative losses in late summer, around the time of the annual minimum in September, with regional variations. The long-term trend over the 1979–2019 period indicates that Arctic summer sea-ice extent has declined at a rate of approximately 13% per decade (Figure 4). In every year from 2016 to 2020, the Arctic average summer minimum and average winter maximum sea-ice extent were below the 1981–2010 long term average. In July 2020, the Arctic sea-ice extent was the lowest on record for July. There is *very high confidence* that Arctic sea-ice extent continues to decline in all months of the year and that since 1979, the areal proportion of thick ice, at least 5 years old, has declined by approximately 90%."); National Snow & Ice Data Center (2 September 2020) *Tapping the brakes*, Arctic Sea Ice News & Analysis ("As of September 1, Arctic sea ice extent stood at 4.26 million square kilometers (1.64 million square miles), the second lowest extent for that date in the satellite passive microwave record that started in 1979."); *and* Bi H., Liang Y., Wang Y., Liang X., Zhang Z., Du T., Yu Q., Huang J., Kong M., & Huang H. (2020) *Arctic multiyear sea ice variability observed from satellites: a review*, J. OCEAN. LIMNOL. 38(4): 962–984, 963 ("As the MY [multiyear] ice in the Arctic Ocean is declining at a significant rate, approximately -9%– -15%/decade in the past three decades (Comiso, 2012; Polyakov et al., 2012; Kwok, 2018), the MY ice area has declined from about two-thirds of the Arctic basin area to less than one third (Galley et al., 2016). Along with the significant decrease in the MY coverage and extent, there is also a clear transitioning trend in MY composition toward the thinner and younger components (Rigor and Wallace, 2004; Maslanik et al., 2007, 2011; Tschudi et al., 2016)."). Analysis by Zack Labe showed that sea ice for the high Arctic (above 80 ºN) was the lowest extent on record: *see* Zack Labe (@ZLabe), Twitter, 11 September 2020, 6:19pm ("Sea ice extent in the middle of the #Arctic Ocean is currently the lowest on record (e.g., high Arctic ~80°N+ latitude). This is a pretty impressive statistic.").

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

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

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

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

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

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

[125] Siegert M. J., Bentley M. J., Atkinson A., Bracegirdle T. J., Convey P., Davies B., Downie R., Hogg A. E., Holmes C., Hughes K. A., Meredith M. P., Ross N., Rumble J., & Wilkinson J. (2023) *Antarctic extreme events*, FRONT. ENVIRON. SCI. 11: 1–15, 4 ("Ice shelves fringe three-quarters of Antarctica's coastline, providing buttressing support that stabilises the rate of ice flow from the grounded ice sheet and its contribution to global sea level (Siegert M. J. et al., 2020) (see Figure 2A for an overview of the ice shelf system). Over the past 5 decades, satellites have observed the retreat, thinning and disintegration of Antarctic ice shelves (Paolo et al., 2015), with change concentrated in two key sectors of the continent. On the Antarctic Peninsula, ice shelves have retreated on average over the last 50 years, with large sections of the LarsenA, Larsen-B, and Wilkins ice shelves collapsing catastrophically in 1995, 2002, and 2008, respectively (Figure 2B, C). Following a period of relative stability in the 1990s, the collapse of the Larsen-B Ice Shelf was triggered by widespread meltwater ponding on the ice shelf surface where crevasse hydrofractures caused pressure-driven disintegration of the shelf in a matter of days (Scambos and Hulbe, 2000). In the austral summer of 2019/20 high levels of surface melting were observed across the Antarctic Peninsula. If such events become more frequent in a warming climate further incidences of ice shelf disintegration may occur. In West Antarctica, dynamic imbalance is driven by incursions of warm modified [Circumpolar Deep Water (CDW)] melting the floating ice shelves (see above), with the interannual and long-term variability of ocean temperatures linked to atmospheric forcing associated with the El Niño-Southern Oscillation (ENSO) (Jenkins et al., 2018). Since 2009, major iceberg calving events have occurred across the continent on ten Antarctic ice shelves, including the Larsen-C, Wordie and Wilkins ice shelves on the Peninsula, Thwaites and Pine Island Glaciers in West Antarctica, and Nansen, Mertz, Brunt, Amery and Conger ice shelves in East Antarctica. Recent studies have suggested that a complex link between atmospheric and ocean processes may have a role to play in ice shelf stability and calving. Extreme atmospheric conditions drive strong winds that can affect ocean swell, which may have had a role in triggering recent iceberg calving (Francis et al., 2021) and historical ice shelf collapse (Massom et al., 2018). Whilst iceberg calving is part of the normal process of mass loss, if calving frequency changes over time it can require decades of regrowth to replace

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the lost ice, and therefore may be an indicator of longer-term change. It is now clear that ice shelves can respond to change over short timescales and that long data records are required to disentangle natural variability from longer term more permanent change."), *discussed in* Koumoundouros T. (22 August 2023) *Antarctic Extremes Are Now Virtually Assured, With Global Ramifications*, SCIENCE ALERT.

[126] Siegert M. J., Bentley M. J., Atkinson A., Bracegirdle T. J., Convey P., Davies B., Downie R., Hogg A. E., Holmes C., Hughes K. A., Meredith M. P., Ross N., Rumble J., & Wilkinson J. (2023) *Antarctic extreme events*, FRONT. ENVIRON. SCI. 11: 1–15, 2–3, 11 ("Antarctic sea ice extent varies annually between a low of 2–4 million km^2, usually in late February, and a September high of 18–20 million km^2 (NSIDC, 2023). Accurate measurements of sea ice extent are available from satellite observations dating back to October 1978. During much of the satellite period, total Antarctic sea-ice extent underwent 'gradual but uneven' increases (Parkinson, 2019), despite the warming global climate and, by contrast, persistent Arctic sea ice loss (Stroeve and Notz, 2018). Indeed, Antarctic sea ice extent hit a record high in winter 2014. However, it then retreated to a record low in summer 2017 (Turner et al., 2017; Parkinson and DiGirolamo, 2021), and the four lowest annual minimum sea ice extents of the satellite era have occurred since, with both 2022 and 2023 setting new records (Figure 1A; NSIDC, 2023). In 2022, the summer minimum extent dropped to below 2 million km^2 for the first time, and winter extent remained at near-record lows for the time of year (Figure 1A). Both the high sea ice extents of 2013–2015 and the low sea ice extents since 2017 lie far outside the observed variability of the baseline period 1981–2010 (Figure 1A), indicating them as 'extreme' based on our existing understanding of the system and highlighting crucial yet poorly understood recent increases in year-to-year variability."; "The examples of Antarctic extreme events vary by geography, realm, spatio-temporal range and, importantly, attribution. Whereas it is an open scientific question as to the level some of these events can be attributed to fossil-fuel burning, in the vast majority of cases it is virtually certain that continued greenhouse gas emissions will lead to increases in the size and frequency of events, even if the causes to date cannot be attributed to it (Table 1). This is particularly concerning because enhanced global heating from fossil-fuel burning is inevitable, to at the very least another 0.4°C (to the 1.5°C Paris limit) on top of historical warming, and possibly much higher if we do not take serious immediate action to curtail emissions. Hence, for the reasons we note, Antarctica's fragile and vulnerable environments may well be subject to considerable stress and damage in future years and decades."), *discussed in* Koumoundouros T. (22 August 2023) *Antarctic Extremes Are Now Virtually Assured, With Global Ramifications*, SCIENCE ALERT ("It's the midst of winter in the Southern Hemisphere and Antarctica is missing an obscene amount of ice. "One might think that the huge remote continent of Antarctica with its kilometers-thick ice sheet could withstand extremes brought about by climate change, but this is absolutely not the case," says University of Leeds glaciologist Anna Hogg. The missing sea ice is currently the size of Greenland, a country that spans nearly 2.2 million square kilometres (836,330 square miles). As a six sigma event, it should only occur once in 7.5 million years. But times are changing. New research led by University of Exeter geophysicist Martin Siegert suggests such extremes are now virtually certain to continue.").

[127] Siegert M. J., Bentley M. J., Atkinson A., Bracegirdle T. J., Convey P., Davies B., Downie R., Hogg A. E., Holmes C., Hughes K. A., Meredith M. P., Ross N., Rumble J., & Wilkinson J. (2023) *Antarctic extreme events*, FRONT. ENVIRON. SCI. 11: 1–15, 2 ("Notably, the most extreme 'heatwave' ever recorded globally occurred over East Antarctica in March 2022 when surface temperature anomalies of up to 38.5° C were observed (Berkeley Earth, 2022)."), *discussed in* Koumoundouros T. (22 August 2023) *Antarctic Extremes Are Now Virtually Assured, With Global Ramifications*, SCIENCE ALERT.

[128] Siegert M. J., Bentley M. J., Atkinson A., Bracegirdle T. J., Convey P., Davies B., Downie R., Hogg A. E., Holmes C., Hughes K. A., Meredith M. P., Ross N., Rumble J., & Wilkinson J. (2023) *Antarctic extreme events*, FRONT. ENVIRON. SCI. 11: 1–15, 2 ("Notably, the most extreme 'heatwave' ever recorded globally occurred over East Antarctica in March 2022 when surface temperature anomalies of up to 38.5° C were observed (Berkeley Earth, 2022). This event was associated with an 'atmospheric river'; a long filament-shaped atmospheric structure that carries abundant moisture across large distances (many hundreds of kilometres), leading to extreme localised heat and precipitation. These atmospheric rivers transport heat and moisture from the subtropics into the heart of the Antarctic continent."), *discussed in* Koumoundouros T. (22 August 2023) *Antarctic Extremes Are Now Virtually Assured, With Global Ramifications*, SCIENCE ALERT.

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[129] Siegert M. J., Bentley M. J., Atkinson A., Bracegirdle T. J., Convey P., Davies B., Downie R., Hogg A. E., Holmes C., Hughes K. A., Meredith M. P., Ross N., Rumble J., & Wilkinson J. (2023) *Antarctic extreme events*, FRONT. ENVIRON. SCI. 11: 1–15, 4 ("Ice shelves fringe three-quarters of Antarctica's coastline, providing buttressing support that stabilises the rate of ice flow from the grounded ice sheet and its contribution to global sea level (Siegert M. J. et al., 2020) (see Figure 2A for an overview of the ice shelf system). Over the past 5 decades, satellites have observed the retreat, thinning and disintegration of Antarctic ice shelves (Paolo et al., 2015), with change concentrated in two key sectors of the continent. On the Antarctic Peninsula, ice shelves have retreated on average over the last 50 years, with large sections of the LarsenA, Larsen-B, and Wilkins ice shelves collapsing catastrophically in 1995, 2002, and 2008, respectively (Figure 2B, C). Following a period of relative stability in the 1990s, the collapse of the Larsen-B Ice Shelf was triggered by widespread meltwater ponding on the ice shelf surface where crevasse hydrofractures caused pressure-driven disintegration of the shelf in a matter of days (Scambos and Hulbe, 2000). In the austral summer of 2019/20 high levels of surface melting were observed across the Antarctic Peninsula. If such events become more frequent in a warming climate further incidences of ice shelf disintegration may occur. In West Antarctica, dynamic imbalance is driven by incursions of warm modified [Circumpolar Deep Water (CDW)] melting the floating ice shelves (see above), with the interannual and long-term variability of ocean temperatures linked to atmospheric forcing associated with the El Niño-Southern Oscillation (ENSO) (Jenkins et al., 2018). Since 2009, major iceberg calving events have occurred across the continent on ten Antarctic ice shelves, including the Larsen-C, Wordie and Wilkins ice shelves on the Peninsula, Thwaites and Pine Island Glaciers in West Antarctica, and Nansen, Mertz, Brunt, Amery and Conger ice shelves in East Antarctica. Recent studies have suggested that a complex link between atmospheric and ocean processes may have a role to play in ice shelf stability and calving. Extreme atmospheric conditions drive strong winds that can affect ocean swell, which may have had a role in triggering recent iceberg calving (Francis et al., 2021) and historical ice shelf collapse (Massom et al., 2018). Whilst iceberg calving is part of the normal process of mass loss, if calving frequency changes over time it can require decades of regrowth to replace the lost ice, and therefore may be an indicator of longer-term change. It is now clear that ice shelves can respond to change over short timescales and that long data records are required to disentangle natural variability from longer term more permanent change."), *discussed in* Koumoundouros T. (22 August 2023) *Antarctic Extremes Are Now Virtually Assured, With Global Ramifications*, SCIENCE ALERT.

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

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

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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).").

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

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

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

[135] Isaksen K., *et al.* (2022) *Exceptional warming over the Barents sea*, SCI. REP. 12(9371): 1–18, 1 ("Both the SAT analysis from instrumental records[8] and widely used reanalyses products, including ERA5, point to a maximum warming area in the Barents region (Fig. 1). This Arctic warming hotspot[10] is not constrained to the warming atmosphere; the Northern Barents Sea (NBS) region also hosts the most pronounced loss of Arctic winter sea ice[11] and has since the early 2000s experienced a sharp increase in both temperature and salinity in the entire water column. The decline in the Barents sea ice cover, increased ocean temperature and salinity are closely related to the higher temperatures in the Atlantic Water and increased ocean heat transport entering the region from the west[12,13,14]. In addition, the increase in salinity is larger towards the upper layers, leading to a weakened ocean stratification and hereby an increased upward heat flux[10]. These oceanographic processes strongly contribute to the amplified warming in the region and enable larger heat flux interaction between the ocean and the air. If the rise in ocean temperature and salinity continues, the originally cold and stratified Arctic shelf region may be transformed into an Atlantic-dominated climate regime with a warmer and more well-mixed water column strongly preventing sea ice formation[10].").

[136] McIntyre M. E. (2023) *Climate tipping points: A personal view*, PHYSICS TODAY 76(3), 44–49, 47 ("When viewed in finer detail, the warming events often seem to have involved more than one sharp stepwise jump within a few decades, with each jump taking only a few years. The mechanisms in play are exceedingly complex. In particular, the warming events are related to global-scale oceanic and atmospheric circulations and sea-ice cover, especially in the Nordic Seas, between Scandinavia and Greenland.[5–8] With one exception, however, the mechanisms considered have

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time scales too long to produce the sharp jumps. The exceptional mechanism—the only mechanism suggested so far that is fast enough—involves the Nordic sea ice and the fine structure of upper-ocean layering underneath the ice.[6,7] The exceptional mechanism depends on the northward inflow of warm, salty subsurface Atlantic water under the sea ice. During cold intervals, the uppermost layers of the Nordic Sea were stably stratified with a strong halocline—a boundary that separates the warm, salty subsurface Atlantic inflow from colder, fresher, more buoyant upper layers capped by sea ice…. But if the subsurface inflow warms enough, the water can become sufficiently buoyant to break through the halocline and up to the surface, where it quickly melts the sea ice. When such sudden sea-ice melting happens over a substantial area, or in steps over a succession of substantial areas, the atmosphere can respond quickly with major changes in its weather patterns on a hemispheric scale. Today some areas in the Arctic Ocean may be approaching a similar state, albeit still short of buoyant breakthrough.[10] Recent underwater observations made in 2003–18 show a weakening halocline being eroded by turbulent mixing, which allows more subsurface heat to reach the surface, at rates that increased from 3–4 W m^{-2} in 2007–08 to about 10 W m^{-2} in 2016–18. As buoyant breakthrough conditions are approached, the current rate of sea-ice melting—already accelerating through the well-known ice-albedo feedback—may likely accelerate further and more drastically. As with the Dansgaard–Oeschger warmings, there could be several such episodes of increased acceleration as different areas of Arctic sea ice are melted in a stepwise fashion. Exactly what will happen is extremely hard to predict since, in climate models, the fine structure of the upper ocean with its halocline and sea ice, the associated buoyancy-related and turbulent-mixing processes, and the subsurface ocean currents and eddies are not accurately represented in enough detail. But an educated guess would be to anticipate a drastic acceleration of Arctic sea-ice loss quite soon, perhaps over the next decade or two, with knock-on effects that could include accelerated melting of the Greenland ice sheet.").

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

[138] Finocchio P. M. & Doyle J. D. (2022) *Summer Cyclones and Their Association With Short-Term Sea Ice Variability in the Pacific Sector of the Arctic*, FRONT. EARTH SCI. 9(738497): 1–17, 15 ("The advective tendency of SIC due to the 10-m wind is one of the most consistent predictors of both local and regional ice loss for the large sample of cyclones in the ECB region. We find the strongest relationship between advection and sea ice loss for low concentration sea ice in August. This supports previous studies arguing that the reduced mechanical strength of lower concentration sea ice makes it more susceptible to wind-induced drift and deformation (Hakkinen et al., 2008; Rampal et al., 2009; Spreen et al., 2011). "). *See also* Finocchio P. M., Doyle J. D., & Stern D. P. (2022) *Accelerated Sea-Ice Loss from Late-Summer Cyclones in the New Arctic*, J. CLIM.: 1–39, 1 ("We compare the 1-7 day changes in sea-ice area and thickness following days in each month with and without cyclones from two decades: 1991-2000 and 2009-2018. Only in August do cyclones locally accelerate seasonal sea-ice loss on average, and the ability of August cyclones to accelerate ice loss has become more pronounced in the recent decade. The recent increase in ice loss following August cyclones is most evident in the Amerasian Arctic (140°E-120°W), where reanalyses indicate that the average upper-ocean temperature has increased by 0.2-0.8°C and the average ice thickness has decreased by almost 1 m between the two decades. Such changes promote cyclone-induced ocean mixing and sea-ice divergence that locally increase the likelihood for rapid ice loss near cyclones. In contrast, June cyclones in both decades locally slow down seasonal sea-ice loss. Moreover, the 7-day sea-ice loss in June has increased from the early to the recent decade by 67% more in the absence of cyclones than in the presence of cyclones. The largest increases in June ice loss occur in the Eurasian Arctic (0-140°E), where substantial reductions in average surface albedo in the recent decade have allowed more of the abundant insolation in the absence of cyclones to be absorbed at the sea surface."). Research is also underway that analyzes 2022 trends for accelerated ice loss in the Arctic due to late summer cyclones: *see* Hand E. (23 August 2022) *Arctic stormchasers brave giant cyclones to understand how they chew up sea ice*, SCIENCE.

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[139] Mallett R. D. C., Stroeve J. C., Cornish S. B., Crawford A. D., Lukovich J. V., Serreze M. C., Barrett A. P., Meier W. N., Heorton H. D. B. S., & Tsamados M. (2021) *Record winter winds in 2020/21 drove exceptional Arctic sea ice transport*, COMMUN. EARTH ENVIRON. 2(149): 1–6, 2 ("The response of the sea ice to the wind forcing was such that four times as much MYI area was transported into the Beaufort Sea as was transported out, but the total ice area transported out was double that transported in (Fig. 2a, b). This transport acted to flush the Beaufort Sea of its first-year ice cover and fill it with MYI. Eight per cent of the Arctic's MYI cover was transported into the Beaufort Sea in winter 2020/2021 (Fig. 2e), contributing to a record fraction of the MYI cover residing in the Beaufort Sea (23.5%) in the last full week of February (Fig. 2f). This fraction has been historically increasing over the data period (1983–2020), however, this high concentration is well above the linear trend (by 2.06 standard deviations; Figs. S9 and S10). Because around two-thirds of the Beaufort Sea has been ice-free on the first of September over the last decade (Fig.2h), this unprecedented concentration of Arctic MYI in the Beaufort Sea puts it at a larger risk of melting."). *See also* Gulev S. K., Thorne P. W., Ahn J., Dentener F. J., Domingues C. M., Gerland S., Gong D., Kaufman D. S., Nnamchi H. C., Quaas J., Rivera J. A., Sathyendranath S., Smith S. L., Trewin B., von Schuckmann K., & Vose R. S. (2021) *Chapter 2: Changing State of the Climate System*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 343 ("A reduction of survival rates of sea ice exported from the Siberian shelves by 15% per decade has interrupted the transpolar drift and affected the long-range transport of sea ice (Krumpen et al., 2019). The thinner and on average younger ice has less resistance to dynamic forcing, resulting in a more dynamic ice cover (Hakkinen et al., 2008; Spreen et al., 2011; Vihma et al., 2012; Kwok et al., 2013).").

[140] Mallett, R. (10 August 2021) *Record-breaking winter winds have blown old Arctic sea ice into the melt zone*, ARCTICTODAY ("In the Arctic, the breakdown of the polar vortex produced an exceptional pattern of surface winds that swirled clockwise about the center of the Arctic Ocean like water around a plughole. These swirling winds spun the floating icepack like a spinning top. In doing so, they drove the Arctic's perennial ice from a relatively safe and cold position north of Greenland into an area where ice increasingly can't survive the summer: the Beaufort Sea. Over the winter, the Beaufort Sea filled with perennial ice such that in the last week of February 2021, it contained a record fraction (23.5 percent) of the Arctic Ocean's total perennial ice cover.").

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

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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.").

[142] Zhang J., Lindsay R., Schweiger A., & Steele M. (2013) *The impact of an intense summer cyclone on 2012 Arctic sea ice retreat*, Geophys. Res. Lett. 40(4): 720–726, 722 ("The rapid reduction in ice volume during the storm is due to enhanced ice melt (Figures 3a–3d). The simulated total ice melt is 0.12 $\times 10^3$ km^3 d^{-1} before the cyclone, but almost doubled during the cyclone, averaging 0.21 $\times$ 10^3 km^3 d^{-1} (or 0.17 $\times$ 10^3 km^3 d^{-1} in the ICAPS) during 6–8 August (Figure 2c and Table 1). The enhanced melt is widespread in the ICAPS, but is strongest in the Canada Basin, where ice melt is as high as 0.12 m d^{-1} (Figures 3b and 3c). This explains the large decrease in ice thickness during the storm in these areas (Figures 1j–1l), up to 0.5 m by 10 August (Figure 1l). The simulated ice in most of these areas was already thin on 4 August before the storm (Figures 1i and 2b)."). *See also* Valkonen E., Cassano J., & Cassano E. (2021) *Arctic Cyclones and their Interactions With the Declining Sea Ice: A Recent Climatology*, J. Geophys. Res. Atmos. 126(12): 1–35, 20 ("We also showed that the increased cyclone counts in the cold season were indeed connected to the declining sea ice in both the warm and cold seasons (Figures 11and A15). Less sea ice in the cold season or the following warm season was related to increased cyclone counts in the cold season."); *and* Finocchio P. M., Doyle J. D., & Stern D. P. (2022) *Accelerated Sea-Ice Loss from Late-Summer Cyclones in the New Arctic*, J. Clim.: 1–39, 1 ("We compare the 1-7 day changes in sea-ice area and thickness following days in each month with and without cyclones from two decades: 1991-2000 and 2009-2018. Only in August do cyclones locally accelerate seasonal sea-ice loss on average, and the ability of August cyclones to accelerate ice loss has become more pronounced in the recent decade. The recent increase in ice loss following August cyclones is most evident in the Amerasian Arctic (140°E-120°W), where reanalyses indicate that the average upper-ocean temperature has increased by 0.2-0.8°C and the average ice thickness has decreased by almost 1 m between the two decades. Such changes promote cyclone-induced ocean mixing and sea-ice divergence that locally increase the likelihood for rapid ice loss near cyclones. In contrast, June cyclones in both decades locally slow down seasonal sea-ice loss. Moreover, the 7-day sea-ice loss in June has increased from the early to the recent decade by 67% more in the absence of cyclones than in the presence of cyclones. The largest increases in June ice loss occur in the Eurasian Arctic (0-140°E), where substantial reductions in average surface albedo in the recent decade have allowed more of the abundant insolation in the absence of cyclones to be absorbed at the sea surface.").

[143] Kim Y.-H., Min S.-K., Gillett N. P., Notz D., & Malinina E. (2023) *Observationally-constrained projections of an ice-free Arctic even under a low emission scenario*, Nat. Commun. 14: 3139, 5 ("Based on the GHG+ scaling factors, we produce observationally-constrained future changes in Arctic SIA under four SSP scenarios. Results indicate that the first sea ice-free September will occur as early as the 2030s–2050s irrespective of emission scenarios. Extended occurrences of an ice-free Arctic in the early summer months are projected later in the century under higher emissions scenarios."). *See also* Docquier D. & Koenigk T. (2021) *Observation-based selection of climate models projects Arctic ice-free summers around 2035*, Commun. Earth Environ. 2(144): 1–8, 4, 6 ("In the high-emission scenario, five out of six selection criteria that include ocean heat transport provide a first ice-free Arctic in September before 2040 (range of multi-model means: 2032–2039), more than 20 years before the date of ice-free Arctic for the multi-model mean without model selection (i.e. 2061) … This model selection reveals that sea-ice area and volume reach lower values at the end of this century compared to the multi-model mean without selection. This arises both from a more rapid reduction in these quantities through this century and from a lower present-day sea-ice area. Using such a model selection, the timing of an almost ice-free Arctic in summer is advanced by up to 29 years in the high-emission scenario, i.e. it could occur as early as around 2035."); Peng G., Matthews J. L., Wang M., Vose R., & Sun L. (2020) *What Do Global Climate Models Tell Us about Future Arctic Sea Ice Coverage Changes?*, Climate 8(15): 1–24, 17 ("Excluding the values later than 2100, the averaged projected [first ice-free Arctic summer year (FIASY)] value for RCP4.5 was 2054 with a spread of 74 years; for RCP8.5, the averaged FIASY was 2042 with a spread of 42 years. … which put the mean FIASY at 2037. The RCP8.5 projections tended to push FIASY earlier, except for those of the MICRO-ESM and MICRO-ESM-CHEM models. Those two models also tended to project earlier Arctic ice-free dates and longer durations."); Overland J. E. & Wang M. (2013) *When will the summer Arctic be nearly sea ice free?*, Geophys. Res. Lett. 40(10): 2097–2101, 2097 ("Three recent approaches to predictions in the scientific literature are as follows: (1) extrapolation of sea ice volume data, (2) assuming several more rapid loss events such as 2007 and

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2012, and (3) climate model projections. Time horizons for a nearly sea ice-free summer for these three approaches are roughly 2020 or earlier, 2030 ± 10 years, and 2040 or later. Loss estimates from models are based on a subset of the most rapid ensemble members. … Observations and citations support the conclusion that most global climate model results in the CMIP5 archive are too conservative in their sea ice projections. Recent data and expert opinion should be considered in addition to model results to advance the very likely timing for future sea ice loss to the first half of the 21st century, with a possibility of major loss within a decade or two."); Guarino M.-V., *et al.* (2020) *Sea-ice-free Arctic during the Last Interglacial supports fast future loss*, Nat. Clim. Change 10: 928–932, 931 ("The predicted year of disappearance of September sea ice under high-emissions scenarios is 2086 for HadCM3 (CMIP3/5), 2048 for HadGEM2-ES (CMIP5) and 2035 for HadGEM3 (CMIP6) (Fig. 4). More broadly, multimodel CMIP3–6 mean predictions (and ranges) for a summer sea-ice-free Arctic are as follows: CMIP3, 2062 (2040–2086); CMIP5, 2048 (2020–2081); and CMIP6, 2046 (2029–2066) (Fig. 4 and Supplementary Table 3). We note that the latest year of sea-ice disappearance for CMIP6 models is 2066 and that 50% of the models predict sea-ice-free conditions between ~2030 and 2040. From this we can see that HadGEM3 is not a particular outlier, in terms of its ECS or projected ice-free year."); *and* Intergovernmental Panel on Climate Change (2021) *Summary for Policymakers*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), Figure SPM.8-b. However, findings of ice-free September Arctic sea ice may be too early by a decade if models are not properly accounting for larger changes in atmospheric circulation, *according to* Topál D. & Ding Q. (2023) *Atmospheric circulation-constrained model sensitivity recalibrates Arctic climate projections*, Nat. Clim. Chang. 1–9, 5 ("To showcase our point, we use the abovementioned method to constrain the timing of the first sea-ice-free September in the SMILEs and CMIP6 models. The cumulative probability density functions (CDFs) corresponding to the time of emergence of the first seasonally sea-ice-free Arctic[52,5]3 (below 1 million km^2 in September) in the raw and the calibrated SIE time series in the model ensembles show prospects of a 9–11-year delay of the 'likely' (in IPCC[54] terms) probability ($P > 0.66$) of a September ice-free Arctic, such that an ice-free summer before 2050 is 'as likely as not' (in IPCC terms $0.33 < P < 0.66$) (Fig. 5c; Methods). This result is in contrast to estimates from previous studies that project ice-free September as early as mid-century[33]. Our results are also at odds with a recent study, where the authors used Arctic temperatures as an emergent constraint on ice-free projections in CMIP6 (ref. 40).").

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

[145] Guarino M.-V., *et al.* (2020) *Sea-ice-free Arctic during the Last Interglacial supports fast future loss*, Nat. Clim. Change 10: 928–932, 929, 931, 932 ("Our study has demonstrated that the high-ECS HadGEM3 model yields a much-improved representation of Arctic summers during the warmer LIG climate compared with previous old-generation model simulations. We analysed simulated surface air temperatures and proxy reconstructions of LIG

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summer temperatures and showed a 95% agreement between the model and observations. Arctic surface temperatures and sea ice are strongly related. By simulating an ice-free summer Arctic, our LIG CMIP6 simulation provides (direct) modelling and (indirect) observational support that the summer Arctic could have been ice free during the LIG. This offers a unique solution to the long-standing puzzle of what occurred to drive the temperatures to rise during LIG Arctic summers. The ability of the HadGEM3 model to realistically simulate the very warm LIG Arctic climate provides independent support for predictions of ice-free conditions by summer 2035. This should be of huge concern to Arctic communities and climate scientists. … The LIG sea-ice decrease commences in June (when the LIG sea-ice extent is outside of the PI range of variability, Fig. 1a) and culminates in a complete loss of ice by the end of the melt season in August and September (Fig. 1a,f). … The predicted year of disappearance of September sea ice under high-emissions scenarios is 2086 for HadCM3 (CMIP3/5), 2048 for HadGEM2-ES (CMIP5) and 2035 for HadGEM3 (CMIP6) (Fig. 4).”).

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

[147] Bonan D. B., Schneider T., Eisenman I., & Wills R. C. J. (2021) *Constraining the Date of a Seasonally Ice-Free Arctic Using a Simple Model*, Geophys. Res. Lett. 48(18): 1–12, 1 (“Under a high-emissions scenario, an ice-free Arctic will likely (>66% probability) occur between 2036 and 2056 in September and between 2050 and 2068 from July to October. Under a medium-emissions scenario, the “likely” date occurs between 2040 and 2062 in September and much later in the 21st century from July to October.”). However, findings of ice-free September Arctic sea ice may be too early by a decade if models are not properly accounting for larger changes in atmospheric circulation, *according to* Topál D. & Ding Q. (2023) *Atmospheric circulation-constrained model sensitivity recalibrates Arctic climate projections*, Nat. Clim. Chang. 1–9, 5 (“To showcase our point, we use the abovementioned method to constrain the timing of the first sea-ice-free September in the SMILEs and CMIP6 models. The cumulative probability density functions (CDFs) corresponding to the time of emergence of the first seasonally sea-ice-free Arctic[52,5]3 (below 1 million km^2 in September) in the raw and the calibrated SIE time series in the model ensembles show prospects of a 9–11-year delay of the ‘likely’ (in IPCC[54] terms) probability ($P > 0.66$) of a September ice-free Arctic, such that an ice-free summer before 2050 is ‘as likely as not’ (in IPCC terms $0.33 < P < 0.66$) (Fig. 5c; Methods). This result is in contrast to estimates from previous studies that project ice-free September as early as mid-century[33]. Our results are also at odds with a recent study, where the authors used Arctic temperatures as an emergent constraint on ice-free projections in CMIP6 (ref. 40).”).

[148] Pistone K., Eisenman I., & Ramanathan V. (2019) *Radiative Heating of an Ice-Free Arctic Ocean*, Geophys. Res. Lett. 46(13): 7474–7480, 7477 (“This heating of 0.71 W/m^2 is approximately equivalent to the direct radiative effect of emitting one trillion tons of CO$_2$ into the atmosphere (see calculation in Appendix A). As of 2016, an estimated 2.4 trillion tons of CO$_2$ have been emitted since the preindustrial period due to both fossil fuel combustion (1.54 trillion tons) and land use changes (0.82 trillion tons), with an additional 40 billion tons of CO$_2$ per year emitted from these sources during 2007–2016 (Le Quéré et al., 2018). Thus, the additional warming due to the complete loss of Arctic

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

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

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

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

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

[153] United States Environmental Protection Agency (2015) U.S. National Black Carbon and Methane Emissions: A Report to the Arctic Council, 2, 9 (Figure 1 shows BC emissions north of the 40th parallel in 2011

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amounting to 0.51 million metric tons, with 39% from open biomass burning, and 51% of that number [19.89% or ~0.10 MMT] due to wildfires; "In 2011, 51 percent of black carbon emissions from open biomass burning were from wildfires, 43 percent from prescribed burning, with the remainder from agricultural field burning."). *See also* Kim J.-S., Kug J.-S., Jeong S.-J., Park H., & Schaepman-Strub G. (2020) *Extensive fires in southeastern Siberian permafrost linked to preceding Arctic Oscillation*, Sci. Adv. 6(2): 1–7, 2, 4 ("Strictly speaking, the fire activity–related high-pressure pattern extends further into southeastern Siberia than the typical AO pattern. This suggests that the AO provides preferable conditions for strong fire activity (i.e., high-temperature anomalies), but the positive pressure anomaly extending westward from the North Pacific to southeastern Siberia explains more southeastern Siberian fire activity variability. … In contrast, we found a significant negative relationship between March to April snow cover and total annual fire activity, as positive temperature anomalies related to a positive AO in February and March drive early snowmelt in March and April with a time lag of 1 to 2 months (Fig. 3, B and C, and fig. S6) (*18*, *19*). This is consistent with results from a snow water equivalent dataset (fig. S7). Accumulated positive temperature anomalies in late winter lead to earlier melting in snow cover's seasonal evolution. Once snow cover is reduced, a positive snow-albedo feedback accelerates surface warming and snowmelt (fig. S8). Thus, significant negative snowmelt is observed in March and April as a result (Fig. 3, B and C). Earlier snowmelt leads to faster exposure of the ground surface and litter, which, in turn, allows favorable conditions for fire spreading because this region consists mostly of larch (*Larix gmelinii*) forests with a high amount of litter that can act as fire fuel (*22*)…. This analysis shows a generally negative relation between burned area and P/PET, meaning that more arid regions have stronger fire activity."); *and* Environmental Protection Agency (2012) *Report to Congress on Black Carbon*, EPA-450/R-12-001.

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

[155] Sharma M., Dickie G., Arranz A., & Scarr S. (8 September 2022) *Why Arctic wildfires are releasing more carbon than ever*, Reuters ("Arctic wildfires that sparked above the 66th parallel north unleashed an estimated 16 million tonnes of carbon in 2021 — roughly equal to the annual carbon dioxide (CO_2) emissions of Peru — according to a report by the Copernicus Climate Change Service.").

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

[157] Chen Y., Romps D. M., Seeley J. T., Veraverbeke S., Riley W. J., Mekonnen Z. A., & Randerson J. T. (2021) *Future increases in Arctic lightning and fire risk for permafrost carbon*, Nat. Clim. Chang. 11(5): 404–410, 407–408 ("Lightning-driven increases in fire may trigger a positive fire–vegetation–soil feedback that promotes shrub

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expansion, northward displacement of the treeline and changes in tree species composition8,25,51,52. A dynamic vegetation feedback may develop over a longer timescale than the atmospheric processes that regulate lightning flash rate and fire ignition. … Together, the vegetation dynamics and changes in fire weather may contribute to a higher ratio of burned area to lightning flash rate north of the treeline than what is currently observed (Extended Data Fig. 8a). After we add this amplifying effect from a vegetation feedback into our simple fire model (by assuming that the ratio of burned area to lightning flash rate in the Arctic tundra will change to the present-day value in boreal forests 480 km south of the treeline, referred to as the ‘dynamic vegetation’ approach), the model predicts a 570 ± 480% enhancement in burned area and carbon release by the end of this century in Arctic tundra. Increases in burned area within Arctic tundra, in turn, may increase the vulnerability of the permafrost carbon reservoir in at least two ways (Fig. 4b). First, more frequent fires have the potential to damage or remove the surface insulating layer of organic matter in areas that have moderate or high fire severity59. The loss of this layer through wildfire combustion will expose the underlying permafrost to substantial warming and degradation8 and lead to thermokarst development in ice-rich permafrost60. …Second, with the expansion of shrubs and northern forests in fire-disturbed areas, surface albedo will probably decline in spring and summer, and the extra energy absorbed by the land surface may further amplify regional climate warming63. … Extra warming and productivity from a fire-driven northward expansion of forests could thus accelerate permafrost thaw and decomposition in areas not currently affected by fire.”). *See also* Witze A. (10 September 2020) *The Arctic is burning like never before — and that’s bad news for climate change*, NATURE NEWS (“Wildfires blazed along the Arctic Circle this summer, incinerating tundra, blanketing Siberian cities in smoke and capping the second extraordinary fire season in a row. By the time the fire season waned at the end of last month, the blazes had emitted a record 244 megatonnes of carbon dioxide — that’s 35% more than last year, which also set records. One culprit, scientists say, could be peatlands that are burning as the top of the world melts.”).

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

[159] Comer B., Olmer N., Mao X., Roy B., & Rutherford D. (2017) *Prevalence of heavy fuel oil and black carbon in Arctic shipping, 2015 to 2025*, International Council on Clean Transportation, 3, 4 (“Studies have analyzed the amount of HFO used and carried in the Arctic. Between 2011 and 2013, Det Norske Vertitas completed a series of reports for the AC’s Protection of the Arctic Marine Environment (PAME) working group to help it understand the use and carriage of HFO in the Arctic (Det Norske Veritas [DNV], 2011, 2013). In these studies, DNV found that only 20% of vessels sailing in the IMO Arctic from August to November 2010, and 28% from January to December 2012, operated on HFO. However, roughly 78%, or 400,000 tonnes, of the bunker fuel mass on board vessels in the IMO Arctic was HFO. DNV found that fishing vessels dominated the Arctic fleet in terms number of ships, operating hours, and fuel consumption in the Arctic; however, they assumed that most of these vessels operated on lighter and cleaner distillate fuels, rather than HFO, a reasonable assumption according to the results presented here. Bulk carriers, passenger vessels, and oil tankers had the most HFO fuel on board by mass because of their larger bunker tank capacity. A recent International Council on Clean Transportation (ICCT) working paper (Comer, Olmer, & Mao, 2016) found that whereas less than half of ships operating in the IMO Arctic used HFO in 2015, the mass of fuel onboard all ships in the IMO Arctic was dominated by HFO (76% HFO; 23% distillate; less than 1% LNG, nuclear, and gas boil of), because ships operating on HFO tend to be larger ships with large bunker fuel tanks. That paper reported that ships in the IMO Arctic in 2015 had more than 830,000 t of HFO onboard, more than twice the amount estimated by DNV for the year 2012. A portion of this substantial increase in fuel carriage is attributable to greater carriage of HFO; however, the bulk of this diference is likely as a result of having more complete ship position and ship characteristics data in the 2016 ICCT study than in the 2013 DNV study. Comer et al. (2016) found that the carriage of HFO as bunker fuel in the IMO Arctic in 2015 was dominated by bulk carriers (247,800 t), container vessels (112,900 t), oil tankers (110,600 t), general cargo vessels (76,600 t), and fishing vessels (76,200 t). … Several studies have estimated BC emissions in the Arctic, although the geographical definitions of the Arctic are inconsistent

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across studies. Corbett et al. (2010) estimated that ships operating in the AMSA area1 emitted 0.88 kilotonnes (kt) of BC in 2004,2 growing to 1.20 kt in 2020, 1.50 kt in 2030, and 2.70 kt in 2050 under a BAU scenario. Similarly, Peters et al. (2011) estimated that ships operating within the AMAP boundary3 emitted 1.15 kt of BC emissions in 2004, growing to 2.16 kt in 2030 and 2.96 kt in 2050. Both studies assumed a BC emission factor (EF) of 0.35 g/kg fuel. Two more recent studies—DNV (2013) and Winther et al. (2014)—better match the geospatial extents of the Arctic found in this report. DNV (2013) estimated that ships operating within the IMO Arctic emitted 0.052 kt of BC in 2012, assuming a BC EF of 0.18 g/kg fuel. Winther et al. (2014) estimated ships operating at or above 58.95°N emitted 1.585 kt of BC in 2012, assuming a BC EF of 0.35 g/kg fuel.”). *See also* Anselmi E. (6 April 2020*) A new report shows that more ships are visiting the Arctic*, ArcticToday; *and* McVeigh K. (10 April 2022) *‘Black carbon’ threat to Arctic as sea routes open up with global heating*, The Guardian.

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

[161] O’Rourke R., Leggett J. A., Comay L. B., Ramseur J. L., Frittelli J., Sheikh P. A., Keating-Bitonti C., & Tracy B. S. (*updated* 24 March 2022) Changes in the Arctic: Background and Issues for Congress, Congressional Research Service R41153, 19 (“While there continues to be significant international cooperation on Arctic issues, the emergence of great power competition (also called strategic competition) between the United States, Russia, and China, combined with the increase in human activities in the Arctic resulting from the diminishment of Arctic ice, has introduced elements of competition and tension into the Arctic’s geopolitical environment,[77] and the Arctic is viewed by some observers as an arena for geopolitical competition among the three countries.[78]”). *See also* Gricius G. (18 March 2021) *Geopolitical Implications of New Arctic Shipping Lanes*, The Arctic Institute; *and* Spohr K. & Hamilton D. S. (eds.) (2020) The Arctic and World Order, Foreign Policy Institute & Henry A. Kissinger Center for Global Affairs, Johns Hopkins University SAIS: Washington, DC.

[162] Rantanen M., Karpechko A. Y., Lipponen A., Nordling K., Hyvärinen O., Ruosteenoja K., Vihma T. & Laaksonen A. (2022) *The Arctic has warmed nearly four times faster than the globe since 1979*, Commun. Earth Environ. 3(168): 1–10, 3 (“During 1979–2021, major portions of the Arctic Ocean were warming at least four times as fast as the global average (Fig. 1c). The most extreme AA values occur in the sea areas near Novaya Zemlya, which were locally warming up to seven times as fast as the global average. These high warming rates are consistent with recent research[44], and evidently, the primary reason for such a high amplification ratio is the reduction of cold-season ice cover, which has been most pronounced in the Barents Sea[44,45]. Furthermore, it has been found that changes in atmospheric circulation have amplified the warming in this area[46,47]. In general, there are no regions within the Arctic Circle where AA[43] is smaller than two, apart from the northern North Atlantic.”), *discussed in* Budryk Z. (11 August 2022) *Arctic warming up to four times as fast as global average: study*, The Hill; *and* Fountain H. (11 August 2022) *Arctic Warming Is Happening Faster Than Described, Analysis Shows*, The New York Times. *See also* Jacobs P., Lenssen N. J. L., Schmidt G. A., & Rohde R. A. (2021) *The Arctic Is Now Warming Four Times As Fast As the Rest of the Globe*, Presentation at the American Geophysical Union Fall Meeting, A13E-02 (“We demonstrate the Arctic is likely warming over 4 times faster than the rest of the world, some 3-4 times the global average, with higher rates found both for more recent intervals as well as more accurate latitudinal boundaries. These results stand in contrast to the widely-held conventional wisdom — prevalent across scientific and lay publications alike — that the Arctic is "only" warming around twice as fast as the global mean.”), *discussed in* Voosen P. (14 December 2021) *The Arctic is warming four times faster than the rest of the world*, Science.

[163] Permafrost Pathways, *Mitigation policy* (*last visited* 9 June 2023) (“Depending on how hot we let it get, carbon emissions from Arctic permafrost thaw are expected to be in the range of 30 to more than 150 billion tons of carbon (110 to more than 550 Gt CO_2) this century, with upper estimates on par with the cumulative emissions from the entire United States at its current rate. To put it another way, permafrost thaw emissions could use up between 25 and 40 percent of the remaining carbon budget that would be necessary to cap warming at the internationally agreed-upon 2 degrees Celsius global temperature threshold established in the Paris Agreement.”); *data from* Schuur E. A. G., McGuire A. D., Schädel C., Grosse G., Harden J. W., Hayes D. J., Hugelius G., Koven C. D., Kuhry P., Lawrence D.

M., Natali S. M., Olefeldt D., Romanovsky V. E., Schaefer K., Turetsky M. R., Treat C. C., & Vonk J. E. (2015) *Climate change and the permafrost carbon feedback*, Nature 520(7546): 171–179.

[164] Annual U.S. CO$_2$ emissions from Figure 1 in U.S. EPA *Climate Change Indicators: U.S. Greenhouse Gas Emissions* (*last visited* 13 June 2023).

[165] Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, Rev. Geophys. 61(e2021RG000757): 1–81, 20 ("Today permafrost covers ∼23 million km2of the planet, with 13–18 × 10^6 km^2 in the Arctic, 1.06 × 10^6 km^2 in the Tibetan plateau and 16–21 × 10^6 km^2 in subsea and Antarctic regions (Chadburn et al., 2017; Gruber, 2012; Sayedi et al., 2020; D. Zou et al., 2017). Total organic carbon content of all permafrost soils in the Northern Hemisphere is assessed to range between 1,460 and 1,700 Gt C, nearly twice the amount of carbon currently in the atmosphere (Olefeldt et al., 2016; Schuur et al., 2018). On a worldwide scale, permafrost carbon represents about one-third of all global soil carbon within the upper 3m (Jobbágy & Jackson, 2000; Schuur et al., 2015)"). *See also* Miner K. R., Turetsky M. R., Malina E., Bartsch A., Tamminen J., McGuire A. D., Fix A., Sweeney C., Elder C. D., & Miller C. E. (2022) *Permafrost carbon emissions in a changing Arctic*, Nat. Rev. Earth Environ. 3: 55–67, 55 ("Permafrost underlies ~25% of the Northern Hemisphere land surface and stores an estimated ~1,700Pg (1,700Gt) of carbon in frozen ground, the active layer and talik[1,2]. Rapid anthropogenic warming and resultant thaw threaten to mobilize permafrost carbon stores[3,4], potentially increasing atmospheric concentrations of carbon dioxide (CO$_2$) and methane (CH$_4$), and converting the Arctic from a carbon sink to a carbon source."); Schuur E. A. G., *et al.* (2015) *Climate Change and the Permafrost Carbon Feedback*, Nature 520: 171–179, 171 ("The first studies that brought widespread attention to permafrost carbon estimated that almost 1,700 billion tons of organic carbon were stored in terrestrial soils in the northern permafrost zone. The recognition of this vast pool stored in Arctic and sub-Arctic regions was in part due to substantial carbon stored at depth (.1 m) in permafrost, below the traditional zone of soil carbon accounting."); *and* World Bank & International Cryosphere Climate Initiative (2013) On Thin Ice: How Cutting Pollution Can Slow Warming and Save Lives, 44.

[166] Schaefer K., Lantuit H., Romanovsky V. E., Schuur E. A. G., & Witt R. (2014) *The Impact of the Permafrost Carbon Feedback on Global Climate*, Environ. Res. Lett. 9(085003): 1–9, 2 ("If temperatures rise and permafrost thaws, the organic material will also thaw and begin to decay, releasing carbon dioxide (CO$_2$) and methane (CH$_4$) into the atmosphere and amplifying the warming due to anthropogenic greenhouse gas emissions … The PCF is irreversible on human time scales because in a warming climate, the burial mechanisms described above slow down or stop, so there is no way to convert CO$_2$ into organic matter and freeze it back into the permafrost."). *See also* Schaefer K., Zhang T., Bruhwiler L., & Barrett A. P. (2011) *Amount and timing of permafrost carbon release in response to climate warming*, Tellus B 63(2): 165–180, 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 CO$_2$ 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 CO$_2$ and methane. This will in turn amplify the rate of atmospheric warming and accelerate permafrost degradation, resulting in a positive PCF feedback loop on climate (Zimov et al., 2006b)."); *and* Chen Y., Liu A., & Moore J.C. (2020) *Mitigation of Arctic permafrost carbon loss through stratospheric aerosol geoengineering*, Nat. Commun. 11(2430): 1–35, 2, 3 ("Between 2020 and 2069, PInc-Panther simulations of soil C change, driven by outputs of 7 ESMs for the RCP4.5 projection, varied from 19.4 Pg C gain to 52.7 Pg C loss (mean 25.6 Pg C loss), while under G4 the ensemble mean was 11.9 Pg C loss (range: 29.2 Pg C gain to 44.9 Pg C loss). Projected C losses are roughly linearly proportional to changes in soil temperature, and each 1 °C warming in the Arctic permafrost would result in ~13.7 Pg C loss; the yintercept indicates that the Arctic permafrost, if maintained in current state, would remain a weak carbon sink. MIROC-ESM and MIROC-ESM-CHEM, with simulations of warming above 3°C, produce severe soil C losses, while GISS-E2-R with minor soil temperature change produces net soil C gains under both scenarios before 2070. … PIncPanTher simulations of the anoxic respiration rates over the period 2006–2010 are 1.2–1.7 Pg C year^{-1}, and so the estimated range of CH$_4$ emissions is 28–39 Tg year^{-1}, which is very close to the 15–40 Tg CH$_4$ year^{-1} estimates of current permafrost wetland CH$_4$ emissions.").

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[167] Wilkerson J., Dobosky R., Sayres D. S., Healy C., Dumas E., Baker B., & Anderson J. G. (2019) *Permafrost nitrous oxide emissions observed on a landscape scale using the airborne eddy-covariance method*, ATMOS. CHEM. PHYS. 19(7): 4257–4268, 4257 ("The microbial by-product nitrous oxide (N_2O), a potent greenhouse gas and ozone depleting substance, has conventionally been assumed to have minimal emissions in permafrost regions. This assumption has been questioned by recent in situ studies which have demonstrated that some geologic features in permafrost may, in fact, have elevated emissions comparable to those of tropical soils. However, these recent studies, along with every known in situ study focused on permafrost N_2O fluxes, have used chambers to examine small areas ($< 50\ m^2$). In late August 2013, we used the airborne eddy-covariance technique to make in situ N_2O flux measurements over the North Slope of Alaska from a low-flying aircraft spanning a much larger area: around 310 km^2. We observed large variability of N_2O fluxes with many areas exhibiting negligible emissions. Still, the daily mean averaged over our flight campaign was 3.8 (2.2–4.7) mg $N_2O\ m^{-2}\ d^{-1}$ with the 90 % confidence interval shown in parentheses. If these measurements are representative of the whole month, then the permafrost areas we observed emitted a total of around 0.04–0.09 g m^{-2} for August, which is comparable to what is typically assumed to be the upper limit of yearly emissions for these regions."). *See also* Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, REV. GEOPHYS. 61(e2021RG000757): 1–81, 23 ("Emissions of nitrous oxide—another potent greenhouse gas—from permafrost also may be non-negligible (Voigt et al., 2020; Wilkerson et al., 2019) and require further study. In general, improved projections of hydrological changes within the permafrost region (Andresen et al., 2020) and better quantification of the rates of permafrost organic carbon mineralization into CO_2 versus CH_4 (or other greenhouse gases such as N_2O), and the fate of permafrost C exported as dissolved organic matter in aquatic environments remain active areas of study with major climate implications (J. C. Bowen et al., 2020; Laurion et al., 2020; Zolkos & Tank, 2020)").

[168] Permafrost Pathways, *Course of Action: Mitigation Policy* (*last visited* 13 June 2023) ("Depending on how hot we let it get, carbon emissions from Arctic permafrost thaw are expected to be in the range of 30 to more than 150 billion tons of carbon (110 to more than 550 Gt CO_2) this century, with upper estimates on par with the cumulative emissions from the entire United States at its current rate. To put it another way, permafrost thaw emissions could use up between 25 and 40 percent of the remaining carbon budget that would be necessary to cap warming at the internationally agreed-upon 2 degrees Celsius global temperature threshold established in the Paris Agreement…. Despite the enormity of this problem, gaps in permafrost carbon monitoring and modeling are resulting in permafrost being left out of global climate policies, rendering our emissions targets fundamentally inaccurate. World leaders are in a race against time to reduce emissions and prevent Earth's temperature from reaching dangerous levels. The problem is, without including current and projected emissions from permafrost, this race will be impossible to finish…. 82% [o]f IPCC models do not include carbon emissions from permafrost thaw."). Annual U.S. CO_2 emissions from Figure 1 in United States Environmental Protection Agency, *Climate Change Indicators: U.S. Greenhouse Gas Emissions* (*last visited* 13 June 2023).

[169] Smith S. L., O'Neill H. B., Isaksen K., Noetzli J., & Romanovsky V. E. (2022) *The changing thermal state of permafrost*, NAT. REV. EARTH ENVIRON. 3: 10–23, 10 ("In warmer permafrost (temperatures close to 0 °C), rates of warming are typically less than 0.3 °C per decade, as observed in sub-Arctic regions. In colder permafrost (temperatures less than −2 °C), by contrast, warming of up to about 1 °C per decade is apparent, as in the high-latitude Arctic. Increased active-layer thicknesses have also been observed since the 1990s in some regions, including a change of 0.4 m in the Russian Arctic."). *See also* Gulev S. K., Thorne P. W., Ahn J., Dentener F. J., Domingues C. M., Gerland S., Gong D., Kaufman D. S., Nnamchi H. C., Quaas J., Rivera J. A., Sathyendranath S., Smith S. L., Trewin B., von Schuckmann K., & Vose R. S. (2021) *Chapter 2: Changing State of the Climate System*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 348 ("Recent (2018–2019) permafrost temperatures in the upper 20–30 m layer (at depths where seasonal variation is minimal) were the highest ever directly observed at most sites (Romanovsky et al., 2020), with temperatures in colder permafrost of northern North America being more than 1°C higher than they were in 1978. Increases in temperature of colder Arctic permafrost are larger (average 0.4°C–0.6°C per decade) than for warmer (temperature >–2° C) permafrost (average 0.17°C per decade) of sub-Arctic regions (Figures 2.25, 9.22).").

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[170] Note that PgC_{eq} for the methane feedback is converted to $GtCO_2eq$ by multiplying by 44/12. Canadell J. G., *et al.* (2021) *Chapter 5: Global Carbon and other Biogeochemical Cycles and Feedbacks*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 728, 737, 739 ("This new assessment, based on studies included in or published since SROCC (Schaefer et al., 2014; Koven et al., 2015c; Schneider von Deimling et al., 2015; Schuur et al., 2015; MacDougall and Knutti, 2016a; Gasser et al., 2018; Yokohata et al., 2020), estimates that the permafrost CO_2 feedback per degree of global warming (Figure 5.29) is 18 (3.1–41, 5th–95th percentile range) PgC $^{o}C^{-1}$. The assessment is based on a wide range of scenarios evaluated at 2100, and an assessed estimate of the permafrost CH_4-climate feedback at 2.8 (0.7–7.3 5th–95th percentile range) Pg C_{eq} $^{o}C^{-1}$ (Figure 5.29). This feedback affects the remaining carbon budgets for climate stabilisation and is included in their assessment (Section 5.5.2). … Beyond 2100, models suggest that the magnitude of the permafrost carbon feedback strengthens considerably over the period 2100–2300 under a high-emissions scenario (Schneider von Deimling et al., 2015; McGuire et al., 2018). Schneider von Deimling et al., (2015) estimated that thawing permafrost could release 20–40 PgC of CO_2 in the period from 2100 to 2300 under a RCP2.6 scenario, and 115–172 PgC of CO_2 under a RCP8.5 scenario. The multi-model ensemble in (McGuire et al., 2018) project a much wider range of permafrost soil carbon losses of 81–642 PgC (mean 314 PgC) for an RCP8.5 scenario from 2100 to 2300, and of a gain of 14 PgC to a loss of 54 PgC (mean loss of 17 PgC) for an RCP4.5 scenario over the same period … Methane release from permafrost thaw (including abrupt thaw) under high-warming RCP8.5 scenario has been estimated at 836–2614 Tg CH_4 over the 21st century and 2800–7400 Tg CH_4 from 2100–2300 (Schneider von Deimling et al., 2015), and as 5300 Tg CH_4 over the 21st century and 16000 Tg CH_4 from 2100–2300 (Turetsky et al., 2020). For RCP4.5, these numbers are 538–2356 Tg CH_4 until 2100 and 2000-6100 Tg CH_4 from 2100–2300 (Schneider von Deimling et al., 2015), and 4100 Tg CH_4 until 2100 and 10000 Tg CH_4 from 2100–2300 (Turetsky et al., 2020) … Land biosphere models show high agreement that long-term warming will increase N_2O release from terrestrial ecosystems (XuRi et al., 2012; B.D. Stocker et al., 2013; Zaehle, 2013; Tian et al., 2019). A positive land N_2O climate feedback is consistent with paleoevidence based on reconstructed and modelled emissions during the last deglacial period (Schilt et al., 2014; H. Fischer et al., 2019; Joos et al., 2020). The response of terrestrial N_2O emissions to atmospheric CO_2 increase and associated warming is dependent on nitrogen availability (van Groenigen et al., 2011; Butterbach-Bahl et al., 2013; Tian et al., 2019). Model-based estimates do not account for the potentially strong emissions increases in boreal and arctic ecosystems associated with future warming and permafrost thaw (Elberling et al., 2010; Voigt et al., 2017). There is medium confidence that the land N_2O climate feedback is positive, but low confidence in the magnitude (0.02 ± 0.01 W m^{-2} $°C^{-1}$). … Other feedback contributions, such as the non-CO_2 biogeochemical feedback, can be converted into a carbon-equivalent feedback term (γ; Section 5.4.5.5, 7.6) by reverse application of the linear feedback approximation (Gregory et al., 2009). The contributions of non-CO_2 biogeochemical feedbacks combine to a linear feedback term of 30 ± 27 PgC_{eq} $°C^{-1}$ (1 standard deviation range, 111 ± 98 Gt CO_2-eq $°C^{-1}$), including a feedback term of –11 [–18 to –5] PgC_{eq} $°C^{-1}$ (5–95% range, –40 [–62 to –18] Gt CO_2-eq $°C^{-1}$) from natural CH_4 and N_2O sources. The biogeochemical feedback from permafrost thaw leads to a combined linear feedback term of -21 ± 12 PgC_{eq} $°C^{-1}$ (1 standard deviation range -77 ± 44 Gt CO_2-eq $°C^{-1}$).").

[171] Hunt K. (14 March 2022) *Holes the size of city blocks are forming in the Arctic seafloor*, CNN ("Marine scientists have discovered deep sinkholes – one larger than a city block of six-story buildings – and ice-filled hills that have formed "extraordinarily" rapidly on a remote part of the Arctic seafloor.").

[172] Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, Rev. Geophys. 61: 1–81, 50 ("Gradual permafrost thaw (Section 2.4) could contribute significant additional carbon emissions over the near-term (92 Gt C by 2100 under RCP8.5) (Meredith et al., 2019). Abrupt permafrost thaw processes acting over faster timescales could emit up to ∼18 Gt C by 2100 including considerable methane (Turetsky et al., 2019, 2020). Over this century, emissions from abrupt thaw could contribute approximately 6,771 Mt CH_4 (Mt C) and 10.95 Gt CO_2 (Gt C) under the worst-case RCP8.5 scenario (Turetsky et al., 2020)."). *See also* Turetsky M. R., Abbott B. W., Jones M. C., Anthony K. W., Olefeldt D., Schuur E. A. G., Grosse G., Kuhry P., Hugelius G., Koven C., Lawrence D. M., Gibson C., Sannel A. B. K., & McGuire A. D. (2020) *Carbon release through abrupt permafrost thaw*, Nat. Geosci. 13(2): 138–143, 139 ("Gradual permafrost thaw (Section 2.4) could contribute significant additional carbon emissions over the near-term (92 Gt C by 2100 under RCP8.5) (Meredith et al., 2019). Abrupt permafrost thaw

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processes acting over faster timescales could emit up to ∼18 Gt C by 2100 including considerable methane (Turetsky et al., 2019, 2020). Over this century, emissions from abrupt thaw could contribute approximately 6,771 Mt CH_4 (Mt C) and 10.95 Gt CO2 (Gt C) under the worst-case RCP8.5 scenario (Turetsky et al., 2020).").

[173] Turetsky M. R., Abbott B. W., Jones M. C., Anthony K. W., Olefeldt D., Schuur E. A. G., Grosse G., Kuhry P., Hugelius G., Koven C., Lawrence D. M., Gibson C., Sannel A. B. K., & McGuire A. D. (2020) *Carbon release through abrupt permafrost thaw*, NAT. GEOSCI. 13: 138–143, 138–139 ("The permafrost zone is expected to be a substantial carbon source to the atmosphere, yet large-scale models currently only simulate gradual changes in seasonally thawed soil. Abrupt thaw will probably occur in <20% of the permafrost zone but could affect half of permafrost carbon through collapsing ground, rapid erosion and landslides. Here, we synthesize the best available information and develop inventory models to simulate abrupt thaw impacts on permafrost carbon balance. Emissions across 2.5 million km^2 of abrupt thaw could provide a similar climate feedback as gradual thaw emissions from the entire 18 million km^2 permafrost region under the warming projection of Representative Concentration Pathway 8.5. While models forecast that gradual thaw may lead to net ecosystem carbon uptake under projections of Representative Concentration Pathway 4.5, abrupt thaw emissions are likely to offset this potential carbon sink. Active hillslope erosional features will occupy 3% of abrupt thaw terrain by 2300 but emit one-third of abrupt thaw carbon losses. Thaw lakes and wetlands are methane hot spots but their carbon release is partially offset by slowly regrowing vegetation. After considering abrupt thaw stabilization, lake drainage and soil carbon uptake by vegetation regrowth, we conclude that models considering only gradual permafrost thaw are substantially underestimating carbon emissions from thawing permafrost. … Our simulations suggest net cumulative abrupt thaw carbon emissions on the order of 80±19PgC by 2300 (Fig. 2a). For context, a recent modelling study found that gradual vertical thaw could result in permafrost carbon losses of 208PgC by 2300 under RCP8.5 (multimodel mean), although model projections ranged from a net carbon gain of 167PgC to a net loss of 641PgC (ref. 2). Thus, our results suggest that abrupt thaw carbon losses are equivalent to approximately 40% of the mean net emissions attributed to gradual thaw. Most of this carbon release stems from newly formed features that cover <5% of the permafrost region"). *See also* Schuur E. A. G., *et al.* (2022) *Permafrost and Climate Change: Carbon Cycle Feedbacks from the Warming Arctic*, ANNU. REV. ENVIRON. RESOUR. 47: 343–371, 351 ("Research at the global scale that links these effects across both lowlands and uplands showed that 20% of the northern permafrost region was considered susceptible to past and future abrupt thaw (47). Importantly, this area also stores 50% of the near-surface soil carbon showing the correlation between carbon and ice accumulation that heightens the risk of abrupt thaw to climate change. Since ESMs do not simulate abrupt thaw, dynamics of ecosystem change including carbon cycling have been represented by a different class of regional models that track soil carbon losses as well as carbon gains from plant growth through ecological succession following abrupt thaw. The most comprehensive of these succession models that included the response of abrupt thaw across uplands and lowlands found that an additional 40% more net ecosystem carbon (80 ± 19 Pg C) would be released by 2300 (48) as compared to the ensemble estimate of net ecosystem carbon release from the PCN-MIP (30), which as described previously, only tracked the effect of gradual top-down permafrost thaw as the climate warms. Most of this additional 40% carbon release is attributed to new abrupt thaw features that cover <5% of the permafrost region. Moreover, plant growth in the succession model offset approximately 20% of the permafrost carbon release, a much lower proportion as compared to the estimate from ESMs in the PCN-MIP. Furthermore, the abrupt thaw succession model could track CH_4, in contrast to the PCN-MIP, which did not, and showed that approximately 20% of the net carbon loss from abrupt thaw could be emitted as CH_4, which contributed 50% of the radiative forcing due to its higher global warming potential. These findings are consistent with other abrupt thaw models that considered subsets of the Arctic permafrost landscape such as lake expansion in lowlands (26, 27)."); *and* Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, REV. GEOPHYS. 61: 1–81, 21 ("The majority of permafrost thaw will occur via thickening of the active layer, often referred to as gradual perma-frost thaw because it affects centimeters of surface permafrost relatively slowly on a time scale of decades to centuries (McGuire et al., 2018; Schneider Von Deimling et al., 2015). Abrupt thaw processes—the collective term for rapid erosion, thermokarst (thaw that leads to subsidence, land slumping, and erosion), and similar phenomena—lead to more abrupt exposure and thaw of permafrost on time scales of days to years (Abbott & Jones, 2015)…Abrupt thaw represents an important ecosystem state change (M. G. Turner et al., 2020) and has the potential to impact <20% of the Arctic region (Olefeldt et al., 2016; Turetsky et al., 2020). Such processes carry implications not just for susceptibility to thaw but also for subsequent rates of carbon release. Carbon mobilized by thermokarst events particularly in Yedoma perma-frost soils (a type of Pleistocene aged

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permafrost) has demonstrated rapid rates of biodegradation, underlining the potential for significant carbon release from thermokarst features (Vonk et al., 2013).").

[174] Abbott B. W., *et al.* (2016) *Biomass offsets little or none of permafrost carbon release from soils, streams, and wildfire: an expert assessment*, ENVIRON. RES. LETT. 11(3): 1–13, 3 ("Precise empirical or model-based assessments of the critical factors driving carbon balance are unlikely in the near future, so to address this gap, we present estimates from 98 permafrost-region experts of the response of biomass, wildfire, and hydrologic carbon flux to climate change. Results suggest that contrary to model projections, total permafrost-region biomass could decrease due to water stress and disturbance, factors that are not adequately incorporated in current models. Assessments indicate that end-of-the-century organic carbon release from Arctic rivers and collapsing coastlines could increase by 75% while carbon loss via burning could increase four-fold. Experts identified water balance, shifts in vegetation community, and permafrost degradation as the key sources of uncertainty in predicting future system response. In combination with previous findings, results suggest the permafrost region will become a carbon source to the atmosphere by 2100 regardless of warming scenario but that 65%–85% of permafrost carbon release can still be avoided if human emissions are actively reduced.").

[175] Schuur E. A. G., *et al.* (2022) *Permafrost and Climate Change: Carbon Cycle Feedbacks from the Warming Arctic*, ANNU. REV. ENVIRON. RESOUR. 47: 343–371, 362 ("The recent appearance of "craters" with high concentrations of CH_4 in some parts of Siberia have raised new questions (133). This phenomenon is a surprise to the permafrost community and appears to be connected with potential CH_4 emissions. Each crater does not contain exceptional levels of CH_4 but could represent new pathways from deep fossil methane that have previously been capped by permafrost. Sources of geologic methane have been observed where ice and permafrost are retreating (116), including subsea (25, 134), and could be new sources to the atmosphere at levels that are only poorly constrained by the projections synthesized in this review.") *See also* Froitzheim N., Majka J., & Zastrozhnov D. (2021) *Methane release from carbonate rock formations in the Siberian permafrost area during and after the 2020 heat wave*, PROC. NAT'L. ACAD. SCI. 118(32): 1–3, 1 ("In the Taymyr Peninsula and surroundings in North Siberia, the area of the worldwide largest positive surface temperature anomaly for 2020, atmospheric methane concentrations have increased considerably during and after the 2020 heat wave. Two elongated areas of increased atmospheric methane concentration that appeared during summer coincide with two stripes of Paleozoic carbonates exposed at the southern and northern borders of the Yenisey-Khatanga Basin, a hydrocarbon-bearing sedimentary basin between the Siberian Craton to the south and the Taymyr Fold Belt to the north. Over the carbonates, soils are thin to nonexistent and wetlands are scarce. The maxima are thus unlikely to be caused by microbial methane from soils or wetlands. We suggest that gas hydrates in fractures and pockets of the carbonate rocks in the permafrost zone became unstable due to warming from the surface. This process may add unknown quantities of methane to the atmosphere in the near future."), *discussed in* Carrington D. (2 August 2021) *Climate crisis: Siberian heatwave led to new methane emissions, study says*, THE GUARDIAN ("The Siberian heatwave of 2020 led to new methane emissions from the permafrost, according to research. Emissions of the potent greenhouse gas are currently small, the scientists said, but further research is urgently needed. Analysis of satellite data indicated that fossil methane gas leaked from rock formations known to be large hydrocarbon reservoirs after the heatwave, which peaked at 6C above normal temperatures. Previous observations of leaks have been from permafrost soil or under shallow seas."), *and* Mufson S. (3 August 2021) *Scientists expected thawing wetlands in Siberia's permafrost. What they found is 'much more dangerous'*, WASHINGTON POST.

[176] Natali S. M., Holdren J. P., Rogers B. M., Treharne R., Duffy P. B., Pomerance R., & MacDonald E. (2021) *Permafrost carbon feedbacks threaten global climate goals*, PROC. NAT'L. ACAD. SCI. 118(21): 1–3, 1 ("This global climate feedback is being intensified by the increasing frequency and severity of Arctic and boreal wildfires (8, 9) that emit large amounts of carbon both directly from combustion and indirectly by accelerating permafrost thaw. Fire-induced permafrost thaw and the subsequent decomposition of previously frozen organic matter may be a dominant source of Arctic carbon emissions during the coming decades (9)."). *See also* Walker X. J., Baltzer J. L., Cumming S. G., Day N. J., Ebert C., Goetz S., Johnstone J. F., Potter S., Rogers B. M., Schuur E. A. G., Turetsky M. R., & Mack M. C. (2019) *Increasing wildfires threaten historic carbon sink of boreal forest soils*, NATURE 572(7770): 520–523, 523 ("The frequency of boreal forest fires is projected to increase even more with expected climate warming and drying28 and, as a result, the total burned area is expected to increase to 130%–350% by mid-century29. These changes will increase the proportion of young forests vulnerable to burning and increase both the loss of legacy C per

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unit area burned and the expanse of forests transitioning from net C uptake over consecutive fire intervals to net C loss.”); *and* Genet H., McGuire A. D., Barrett K., Breen A., Euskirchen E. S., Johnstone J. F., Kasischke E. S., Melvin A. M., Bennett A., Mack M. C., Rupp T. S., Schuur A. E. G., Turetsky M. R., & Yuan F. (2013) *Modeling the effects of fire severity and climate warming on active layer thickness and soil carbon storage of black spruce forests across the landscape in interior Alaska*, ENVIRON. RES. LETT. 8(4): 1–13, 2 (“In simulations that included the effects of both warming and fire at the regional scale, fire was primarily responsible for a reduction in organic layer thickness of 0.06 m on average by 2100 that led to an increase in active layer thickness of 1.1 m on average by 2100. The combination of warming and fire led to a simulated cumulative loss of 9.6 kgC m−2 on average by 2100. Our analysis suggests that ecosystem carbon storage in boreal forests in interior Alaska is particularly vulnerable, primarily due to the combustion of organic layer thickness in fire and the related increase in active layer thickness that exposes previously protected permafrost soil carbon to decomposition.”).

[177] Natali S. M., Holdren J. P., Rogers B. M., Treharne R., Duffy P. B., Pomerance R., & MacDonald E. (2021) *Permafrost carbon feedbacks threaten global climate goals*, PROC. NAT’L. ACAD. SCI. 118(21): 1–3, 1 (“Fire-induced permafrost thaw and the subsequent decomposition of previously frozen organic matter may be a dominant source of Arctic carbon emissions during the coming decades (9)”).

[178] Hjort J., Streletskiy D., Doré G., Wu Q., Bjella K., & Luoto M. (2022) *Impacts of permafrost degradation on infrastructure*, NAT. REV. EARTH ENVIRON. 3: 24–38, 24 (“Permafrost change imposes various threats to infrastructure, namely through warming, active layer thickening and thaw-related hazards such as thermokarst and mass wasting. These impacts, often linked to anthropogenic warming, are exacerbated through increased human activity. Observed infrastructure damage is substantial, with up to 80% of buildings in some Russian cities and ~30% of some road surfaces in the Qinghai–Tibet Plateau reporting damage. Under anthropogenic warming, infrastructure damage is projected to continue, with 30–50% of critical circumpolar infrastructure thought to be at high risk by 2050. Accordingly, permafrost degradation-related infrastructure costs could rise to tens of billions of US dollars by the second half of the century.”). *See also* Hjort J., Karjalainen O., Aalto J., Westermann S., Romanovsky V. E., Nelson F. E., Etzelmüller B., & Luoto M. (2018) *Degrading permafrost puts Arctic infrastructure at risk by mid-century*, NAT. COMMUN. 9(5147): 1–9, 1 (“Here we identify at unprecedentedly high spatial resolution infrastructure hazard areas in the Northern Hemisphere’s permafrost regions under projected climatic changes and quantify fundamental engineering structures at risk by 2050. We show that nearly four million people and 70% of current infrastructure in the permafrost domain are in areas with high potential for thaw of near-surface permafrost. Our results demonstrate that one-third of pan-Arctic infrastructure and 45% of the hydrocarbon extraction fields in the Russian Arctic are in regions where thaw-related ground instability can cause severe damage to the built environment. Alarmingly, these figures are not reduced substantially even if the climate change targets of the Paris Agreement are reached.”).

[179] Staalesen A. (29 June 2021) *The looming Arctic collapse: More than 40% of north Russian buildings are starting to crumble*, ARCTIC TODAY (“Aleksandr Kozlov, Russia’s Minister of Natural Resources, told a minister’s council in May that more than 40% of the northern region’s buildings are starting to deform. Nearly 30% of oil and gas installations are inoperable. By 2050, Russian researchers estimate that the melting permafrost will inflict damages worth about $69 billion, about a quarter of the current Russian federal budget.”).

[180] Langer M., von Deimling T. S., Westermann S., Rolph R., Rutte R., Antonova S., Rachold V., Schultz M., Oehme A., & Grosse G. (2023) *Thawing permafrost poses environmental threat to thousands of sites with legacy industrial contamination*, NAT. COMMUN. 14(1721): 1–11, 1 (“Here we identify about 4500 industrial sites where potentially hazardous substances are actively handled or stored in the permafrost-dominated regions of the Arctic. Furthermore, we estimate that between 13,000 and 20,000 contaminated sites are related to these industrial sites. Ongoing climate warming will increase the risk of contamination and mobilization of toxic substances since about 1100 industrial sites and 3500 to 5200 contaminated sites located in regions of stable permafrost will start to thaw before the end of this century.”). *See also* Wu R., Trubl G., Taş N., & Jansson J. K. (2022) *Permafrost as a potential pathogen reservoir*, ONE EARTH 5(4): 351–360, 351 (“The Arctic is currently warming at unprecedented rates because of global climate change, resulting in thawing of large tracts of permafrost soil. A great challenge is understanding the implications of permafrost thaw on human health and the environment. Permafrost is a reservoir of mostly uncharacterized microorganisms and viruses, many of which could be viable.”).

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[181] *See* Wadhams P. (2017) A Farewell to Ice: A Report from the Arctic, Oxford University Press. *See also* Shakohva N., Semiletov I., & Chuvilin E. (2019) *Understanding the Permafrost-Hydrate System and Associated Methane Releases in the East Siberian Arctic Shelf*, Geosci. 9(251): 1–23; *and* Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, Rev. Geophys. 61: 1–81, 13 ("Early estimates of high rates of methane emissions from hydrate dissociation on the East Siberian Arctic Shelf (Shakhova et al., 2014) have been revised substantially downwards by numerous subsequent studies (Berchet et al., 2016; Thornton et al., 2016, 2020; Tohjima et al., 2020). Present-day marine methane release from Arctic hydrate dissociation is probably primarily of natural origin, resulting from the pressure decrease associated with isostatic uplift following the last glacial maximum, rather than a response to anthropogenic forcing (Wallmann et al., 2018). And in the Beaufort Sea, fossil methane possibly from hydrate emissions was observed in deeper waters but was removed, likely via oxidation, prior to atmospheric emission (Sparrow et al., 2018). In conclusion, while levels of warming exist beyond which large quantities of methane in hydrate deposits may eventually become destabilized, numerous physical, thermodynamic, chemical, and biological factors combine to substantially limit the rate at which this methane might escape to the atmosphere. For more moderate warming of ~2°C, methane hydrates might well exert a negligible overall impact on atmospheric temperatures. Methane hydrate dissociation would additionally take place on extremely long timescales of millennia, rather than over abrupt or fast timescales that would produce an acute warming spike…. With all of this in mind, in relation to other candidate tipping elements covered within this review, marine methane hydrates represent a relatively lower-impact climate feedback especially for warming in the Anthropocene (Table 3).").

[182] Weldeab S., Schneider R. R., Yu J., & Kylander-Clark A. (2022) *Evidence for massive methane hydrate destabilization during the penultimate interglacial warming*, Proc. Nat'l. Acad. Sci. 119(35): 1–9, 7 ("While further studies are needed to determine the extent of methane hydrate destabilization during the weakened AMOC interval of the Eemian, the consequence of broad methane hydrate destabilization is increased atmospheric CH_4 and CO_2 concentrations. Taking age model uncertainties into consideration, during the peak in anomalously low carbon isotopes, the atmospheric CO_2 and CH_4 concentrations rose by 17 to 10 parts per million per volume and 20 parts per billion per volume, respectively (SI Appendix, Fig. S9) (49–51). Although the magnitude of this change varies between ice cores and analytical laboratories, the $\delta^{13}C$ values of atmospheric CO_2 declined by 0.3 to 0.4‰ coeval with the $\delta^{13}C$ anomaly recorded in the Gulf of Guinea sediment sequence (SI Appendix, Fig. S9) (50, 52), indicating that a source with a significantly negative $\delta^{13}C$ signature contributed to the increase of atmospheric CO_2. Methane release and methane oxidation due to massive methane hydrate destabilization is the likely source."). *See also* Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, Rev. Geophys. 61: 1–81, 10–11 ("A significant time lag separates atmospheric warming due to climate change and the much longer timescales required for transport and diffusion of heat anomalies into the ocean and sediment. As sediment warming is required for methane hydrate instability, dissociation may not be initiated until centuries to millennia after the requisite warming spike (Archer, 2015; Archer et al., 2009; K. Kretschmer et al., 2015; Ruppel, 2011). For deep ocean sediments, tens of millennia might be required for the methane hydrate zone to begin appreciably warming, let alone for hydrate to begin dissociating (Archer et al., 2009; Ruppel, 2011). This factor does not preclude eventual significant release of carbon from methane hydrate, but does mean that this climate feedback occurs with a very substantial delay between commitment and realization.").

[183] Whiteman G., Hope C., & Wadhams P. (2013) *Vast costs of Arctic change*, Nature 499(7459): 401–403, 401–403 ("We calculate that the costs of a melting Arctic will be huge, because the region is pivotal to the functioning of Earth systems such as oceans and the climate. The release of methane from thawing permafrost beneath the East Siberian Sea, off northern Russia, alone comes with an average global price tag of $60 trillion in the absence of mitigating action — a figure comparable to the size of the world economy in 2012 (about $70 trillion). The total cost of Arctic change will be much higher… The methane pulse will bring forward by 15–35 years the average date at which the global mean temperature rise exceeds 2°C above pre-industrial levels — to 2035 for the business-as-usual scenario and to 2040 for the low-emissions case (see 'Arctic methane'). This will lead to an extra $60 trillion (net present value) of mean climate-change impacts for the scenario with no mitigation, or 15% of the mean total predicted cost of climate-change impacts (about $400 trillion). In the low-emissions case, the mean net present value of global

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climate-change impacts is $82 trillion without the methane release; with the pulse, an extra $37 trillion, or 45% is added…. These costs remain the same irrespective of whether the methane emission is delayed by up to 20 years, kicking in at 2035 rather than 2015, or stretched out over two or three decades, rather than one. A pulse of 25 Gt of methane has half the impact of a 50 Gt pulse. The economic consequences will be distributed around the globe, but the modelling shows that about 80% of them will occur in the poorer economies of Africa, Asia and South America. … The full impacts of a warming Arctic, including, for example, ocean acidification and altered ocean and atmospheric circulation, will be much greater than our cost estimate for methane release alone. To find out the actual cost, better models are needed to incorporate feedbacks that are not included ….”). *See also* Wadhams P. (2017) A FAREWELL TO ICE: A REPORT FROM THE ARCTIC, Oxford University Press; *and* Shakohva N., Semiletov I., & Chuvilin E. (2019) *Understanding the Permafrost-Hydrate System and Associated Methane Releases in the East Siberian Arctic Shelf*, GEOSCI. 9(6): 251, 1–23.

[184] Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, REV. GEOPHYS. 61: 1–81, 13 (“Early estimates of high rates of methane emissions from hydrate dissociation on the East Siberian Arctic Shelf (Shakhova et al., 2014) have been revised substantially downwards by numerous subsequent studies (Berchet et al., 2016; Thornton et al., 2016, 2020; Tohjima et al., 2020). Present-day marine methane release from Arctic hydrate dissociation is probably primarily of natural origin, resulting from the pressure decrease associated with isostatic uplift following the last glacial maximum, rather than a response to anthropogenic forcing (Wallmann et al., 2018). And in the Beaufort Sea, fossil methane possibly from hydrate emissions was observed in deeper waters but was removed, likely via oxidation, prior to atmospheric emission (Sparrow et al., 2018. … In conclusion, while levels of warming exist beyond which large quantities of methane in hydrate deposits may eventually become destabilized, numerous physical, thermodynamic, chemical, and biological factors combine to substantially limit the rate at which this methane might escape to the atmosphere. For more moderate warming of ~2°C, methane hydrates might well exert a negligible overall impact on atmospheric temperatures. Methane hydrate dissociation would additionally take place on extremely long timescales of millennia, rather than over abrupt or fast timescales that would produce an acute warming spike…. With all of this in mind, in relation to other candidate tipping elements covered within this review, marine methane hydrates represent a relatively lower-impact climate feedback especially for warming in the Anthropocene (Table 3).”).

[185] Ye W., Li Y., Wen J., Zhang J., Shakhova N., Liu J., Wu M., Semiletov I., & Zhan L. (2023) *Enhanced Transport of Dissolved Methane From the Chukchi Sea to the Central Arctic*, GLOB. BIOGEOCHEM. CYCLES 37(2): 1–21, 2 (“Here, based on our integrated data set (including 420 samples) and combined with previous studies (including 238 data points) (Fenwick et al., 2017; Kudo et al., 2018; Li et al., 2017; Lorenson et al., 2016), we find that CH_4 was significantly enhanced in the Chukchi Sea and distributed northward with the shelf-break jet, providing clear evidence of increased CH_4 transport from the Chukchi Sea shelf to the central Arctic in the 2010s compared with the 1990s.”).

[186] Wadham J. L., Hawkings J. R., Tarasov L., Gregoire L. J., Spencer R. G. M., Gutjahr M., Ridgwell A., & Kohfeld K. E. (2019) *Ice sheets matter for the global carbon cycle*, NAT. COMMUN. 10(3567): 1–17, 8–9 (“There are substantial uncertainties regarding the magnitude of present day sub-ice sheet CH_4 hydrate reserves because of the difficulties of accessing sediments in subglacial sedimentary basins. Global subglacial methane hydrate stocks at the present day are likely to be dominated by those in Antarctic sedimentary basins (estimated at up to 300 Pg C as methane hydrate and free gas95). At the LGM, the global sub-ice sheet hydrate reserve could have been much larger (>500 Pg C, 20% of the present day marine hydrate stocks), with hydrate also present beneath former northern hemisphere ice sheets17,18,122 (see Fig. 4 for details and calculation methods). The vulnerability of Antarctic subglacial CH_4 hydrate reserves to destabilization is high because of their predicted location around the continent’s periphery in sedimentary basins where ice thinning in a warming climate is probable.”). *See also* Dessandier P.-A., Knies J., Plaza-Faverola A., Labrousse C., Renoult M., & Panieri G. (2021) *Ice-sheet melt drove methane emissions in the Arctic during the last two interglacials*, GEOLOGY 49(7): 799–803, 799 (“Here, we argue that based on foraminiferal isotope studies on drill holes from offshore Svalbard, methane leakage occurred upon the abrupt Eurasian ice-sheet wastage during terminations of the last (Weichselian) and penultimate (Saalian) glaciations. Progressive increase of methane emissions seems to be first recorded by depleted benthic foraminiferal $\delta^{13}C$. This is quickly followed by the precipitation of methane-derived authigenic carbonate as overgrowth inside and outside foraminiferal shells,

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characterized by heavy $\delta^{18}O$ and depleted $\delta^{13}C$ of both benthic and planktonic foraminifera. The similarities between the events observed over both terminations advocate a common driver for the episodic release of geological methane stocks. Our favored model is recurrent leakage of shallow gas reservoirs below the gas hydrate stability zone along the margin of western Svalbard that can be re-activated upon initial instability of the grounded, marine-based ice sheets. Analogous to this model, with the current acceleration of the Greenland ice melt, instabilities of existing methane reservoirs below and nearby the ice sheet are likely."); *and* Kleber G. E., Hodson A. J., Magerl L., Mannerfelt E. S., Bradbury H. J., Zhu Y., Trimmer M., & Turchyn A. V. (2023) *Groundwater springs formed during glacial retreat are a large source of methane in the high Arctic*, NAT. GEOSCI. 1–8, 5 ("Expected annual emissions from proglacial springs within the region range from 27 t yr^{-1} CH_4 (±0.14 t) to 230 t yr^{-1} CH_4 (±1.1 t), which equates to emissions of up to 37 kg km^{-2} yr^{-1} CH_4 (±2 kg km^{-2} yr^{-1} CH_4). When we extrapolate this across the Svalbard archipelago without accounting for regional differences in geology, methane emissions associated with proglacial groundwater springs could be up to 2.31 kt yr^{-1} CH_4 (±0.14 kt yr^{-1} CH_4).").

[187] Watts J. (27 October 2020) *Arctic methane deposits 'starting to release', scientists say*, THE GUARDIAN ("'At this moment, there is unlikely to be any major impact on global warming, but the point is that this process has now been triggered. This East Siberian slope methane hydrate system has been perturbed and the process will be ongoing,' said the Swedish scientist Örjan Gustafsson, of Stockholm University, in a satellite call from the vessel."); *discussing* the International Siberian Shelf Study (ISSS) 2020 Arctic Ocean Expedition. *See also* Smith E. (18 February 2020) *NASA Flights Detect Millions of Arctic Methane Hotspots*, National Aeronautics and Space Administration.

[188] Steinbach J., Holmstrand H., Shcherbakova K., Kosmach D., Brüchert V., Shakhova N., Salyuk A., Sapart C. J., Chernykh D., Noormets R., Semiletov I., & Gustafsson Ö. (2021) *Source apportionment of methane escaping the subsea permafrost system in the outer Eurasian Arctic Shelf*, PROC. NAT'L. ACAD. SCI. 118(10): 1–9, 7 ("Taken together, the triple-isotope data presented here, in combination with other system data and indications from earlier studies, suggest that deep thermogenic reservoirs are key sources of the elevated methane concentrations in the outer Laptev Sea. This finding is essential in several ways: The occurrence of elevated levels of radiocarbon-depleted methane in the water column may be an indication of thawing subsea permafrost in the study area (see also ref. 8). The triple-isotope fingerprinting suggests, however, that methane may not primarily originate directly from the subsea permafrost; the continuous leakage of an old geological reservoir to the water column suggests the existence of perforations in the subsea permafrost, serving as conduits of deeper methane to gas-charged shallow sediments. Second, the finding that methane is released from a large pool of preformed methane, as opposed to methane from slow decomposition of thawing subsea permafrost organic matter, suggests that these releases may be more eruptive in nature, which provides a larger potential for abrupt future releases."). *See also* Wild B., Shakhova N., Dudarev O., Ruban A., Kosmach D., Tumskoy V., Tesi T., Grimm H., Nybom I., Matsubara F., Alexanderson H., Jakobsson M., Mazurov A., Semiletov I., & Gustafsson Ö. (2022) *Organic matter composition and greenhouse gas production of thawing subsea permafrost in the Laptev Sea*, NAT. COMMUN. 13(5057): 1–12, 7 ("The lower rates of CH_4 production by subsea permafrost decomposition estimated here, and the likely oxidation of part of this CH_4, do not point to a dominant contribution of organic matter decomposition in thawed subsea permafrost to the high emissions observed in the area. We emphasize, however, the high variability of observed CH_4 production rates, and the limitations of upscaling from incubations to natural environments. Taken together, the high CH_4 emissions ubiquitously observed in the field likely stem from other sources such as preformed CH_4 in gas pockets in the subsea permafrost, collapsing CH_4 hydrates, or venting of a deep thermogenic CH_4 pool.").

[189] Dyonisius M. N., *et al.* (2020) *Old carbon reservoirs were not important in the deglacial methane budget*, SCIENCE 367(6480): 907–910, 908–909 ("Resulting CH_4 emissions from old permafrost carbon range from 0 to 53 Tg CH_4 per year (table S10) (20) throughout the last deglaciation and may have contributed up to 27% of the total CH_4 emissions to the atmosphere (95% CI upper limit) at the end of the OD-B transition (14.42 ka BP). However, we consider this calculation speculative (see section 4.3 of the materials and methods) (20)…. The last deglaciation serves only as a partial analog to current anthropogenic warming, with the most important differences being the much colder baseline temperature, lower sea level, and the presence of large ice sheets covering a large part of what are currently permafrost regions in the NH…. Because the relatively large global warming of the last deglaciation (which included periods of large and rapid regional warming in the high latitudes) did not trigger CH_4 emissions from old carbon reservoirs, such CH_4 emissions in response to anthropogenic warming also appear to be unlikely."). *See also* Canadell J. G., *et al.*

(2021) *Chapter 5: Global Carbon and other Biogeochemical Cycles and Feedbacks*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 5-80 ("The present-day methane release from shelf clathrates is <10 TgCH$_4$ yr^{-1} (Kretschmer et al., 2015; Saunois et al., 2020). Despite polar amplification (Chapter 7), substantial releases from the permafrost-embedded subsea clathrates is very unlikely (Minshull et al., 2016; Malakhova and Eliseev, 2017, 2020). This is consistent with an overall small release of methane from the shelf clathrates during the last deglacial despite large reorganisations in climate state (Bock et al., 2017; Petrenko et al., 2017; Dyonisius et al., 2020). The long timescales associated with clathrate destabilisation makes it unlikely that CH$_4$ release from the ocean to the atmosphere will deviate markedly from the present-day value through the 21st century (Hunter et al., 2013), corresponding to no more than additional 20 ppb of atmospheric methane (i.e. <0.2 ppb yr^{-1} 52).").

[190] Armstrong McKay D. I., Staal A., Abrams J. F., Winkelmann R., Sakschewski B., Loriani S., Fetzer I., Cornell S. E., Rockström J., & Lenton T. M. (2022) *Exceeding 1.5°C global warming could trigger multiple climate tipping points*, Science 377(6611): 1–10, 7 ("Current warming is ~1.1°C above preindustrial and even with rapid emission cuts warming will reach ~1.5°C by the 2030s (23). We cannot rule out that WAIS and GrIS tipping points have already been passed (see above) and several other tipping elements have minimum threshold values within the 1.1 to 1.5°C range. Our best estimate thresholds for GrIS, WAIS, REEF, and abrupt permafrost thaw (PFAT) are ~1.5°C although WAIS and GrIS collapse may still be avoidable if GMST returns below 1.5°C within an uncertain overshoot time (likely decades) (94)."). *See also* Wunderling N., Winkelmann R., Rockström J., Loriani S., Armstrong-McKay D., Ritchie P., Sakschewski B., & Donges J. (2023) *Global warming overshoots increase risks of climate tipping cascades in a network model*, Nat. Clim. Chang. 13: 75–82, 75 ("Current policies and actions make it very likely, at least temporarily, to overshoot the Paris climate targets of 1.5–<2.0 °C above pre-industrial levels. If this global warming range is exceeded, potential tipping elements such as the Greenland Ice Sheet and Amazon rainforest may be at increasing risk of crossing critical thresholds. This raises the question of how much this risk is amplified by increasing overshoot magnitude and duration. Here we investigate the danger for tipping under a range of temperature overshoot scenarios using a stylized network model of four interacting climate tipping elements. Our model analysis reveals that temporary overshoots can increase tipping risks by up to 72% compared with non-overshoot scenarios, even when the long-term equilibrium temperature stabilizes within the Paris range. Our results suggest that avoiding high-end climate risks is possible only for low-temperature overshoots and if long-term temperatures stabilize at or below today's levels of global warming."); *and* Intergovernmental Panel on Climate Change (2023) AR6 Synthesis Report: Climate Change 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 42 ("Risks associated with large-scale singular events or tipping points, such as ice sheet instability or ecosystem loss from tropical forests, transition to high risk between 1.5°C–2.5°C (*medium confidence*) and to very high risk between 2.5°C–4°C (*low confidence*). The response of biogeochemical cycles to anthropogenic perturbations can be abrupt at regional scales and irreversible on decadal to century time scales (*high confidence*). The probability of crossing uncertain regional thresholds increases with further warming (*high confidence*).").

[191] DeConto R. M., Pollard D., Alley R. B., Velicogna I., Gasson E., Gomez N., Sadai S., Condron A., Gilford D. M., Ashe E. L., Kopp R. E., Li D., & Dutton A. (2021) *The Paris Climate Agreement and future sea-level rise from Antarctica*, Nature 593(7857): 83–89, 88 ("We find that without future warming beyond 2020, Antarctica continues to contribute to 21st-century sea-level rise at a rate roughly comparable to today's, producing 5 cm of GMSL (Global Mean Sea Level) rise by 2100 and 1.34 m by 2500 (Fig. 3, Table 1). Simulations initially following the +3 °C pathway, but with subsequent CDR (carbon dioxide reduction/negative emissions) delayed until after 2060, show a sharp jump in the pace of 21st-century sea-level rise (Fig. 3b). Every decade that CDR mitigation is delayed has a substantial long-term consequence on sea level, despite the fast decline in CO$_2$ and return to cooler temperatures (Fig. 3c). Once initiated, marine-based ice loss is found to be unstoppable on these timescales in all mitigation scenarios (Fig. 3). The commitment to sustained ice loss is caused mainly by the onset of marine ice instabilities triggered by the loss of ice shelves that cannot recover in a warmer ocean with long thermal memory (Fig. 3c)."). *See also* Pattyn F., *et al.* (2018) *The Greenland and Antarctic ice sheets under 1.5 °C global warming*, Nat. Clim. Change 8(12): 1053–1061, 1053 ("On millennial timescales, both ice sheets have tipping points at or slightly above the 1.5–2.0 °C threshold; for

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Greenland, this may lead to irreversible mass loss due to the surface mass balance–elevation feedback, whereas for Antarctica, this could result in a collapse of major drainage basins due to ice-shelf weakening.”).

[192] Ripple W. J., Wolf C., Newsome T. M., Gregg J. W., Lenton T. M., Palomo I., Eikelboom J. A. J., Law B. E., Huq S., Duffy P. B., & Rockström J. (2021) *World Scientists’ Warning of a Climate Emergency 2021*, BioSci. 71(9): 894–898, 896 (“Greenland and Antarctica recently showed new year-to-date alltime record low levels of ice mass (figure 2f, 2g). In 2020, the minimum summer Arctic sea ice was at its second smallest extent on record, and glacier thickness also set a new all-time low (figure 2e, 2h). Glaciers are melting much faster than previously believed; they are losing 31% more snow and ice per year than they did just 15 years ago (Hugonnet et al. 2021).”).

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

[194] King M. D., Howat I. M., Candela S. G., Noh M. J., Jeong S., Noël B. P. Y., van den Broeke M. R., Wouters B., & Negrete A. (2020) *Dynamic ice loss from the Greenland Ice Sheet driven by sustained glacier retreat*, Comm. Earth & Env’t.: 1–7, 1 (“The Greenland Ice Sheet is losing mass at accelerated rates in the 21st century, making it the largest single contributor to rising sea levels. Faster flow of outlet glaciers has substantially contributed to this loss, with the cause of speedup, and potential for future change, uncertain.”).

[195] Box J. E., Hubbard A., Bahr D. B., Colgan W. T., Fettweis X., Mankoff K. D., Wehrlé A., Noël B., van den Broeke M. R., Wouters B., Bjørk A. A., & Fausto R. S. (2022) *Greenland ice sheet climate disequilibrium and committed sea-level rise*, Nat. Clim. Change: 808–818, 809, 812 (“Application of the average 2000–2019, hereafter ‘recent’, climatology to Greenland’s entire glacierized area of 1,783,090 km^2 gives an AAR/AAR$_0$ (α) disequilibrium with the current ice configuration corresponding with a $3.3 \pm 0.8\%$ committed area and volume loss. Taken in perpetuity, this imbalance with recent climate results in $59 \pm 15 \times 10^3$ km^2 of committed retreat of Greenland’s ice area, equivalent to $110 \pm 27 \times 10^3$ km^3 of the ice sheet volume or 274 ± 68 mm of global eustatic SLR. … Given the breadth and potency of those processes, we contend that known physical mechanisms can deliver most of the committed ice volume loss from Greenland’s disequilibrium with its recent climate within this century. Nevertheless, we underscore that a SLR of at least 274 ± 68 mm is already committed, regardless of future climate warming scenarios.”), *discussed in* Mooney C. (29 August 2022) *Greenland ice sheet set to raise sea levels by nearly a foot, study finds*, The Washington Post; *and* Funes Y. (29 August 2022) *The Greenland Ice Sheet’s Terrifying Future*, Atmos.

[196] Nature Research Briefing (2023) *How rapidly can ice sheets retreat?*, Nature, 1 (“Our results demonstrate that ice sheets can retreat at up to 600 metres per day — 20 times faster than the highest rate observed in Antarctica by satellites1. Furthermore, our findings reveal the vulnerability of regions of ice sheets with flat beds (those shallower than 1°) to pulses of extremely rapid retreat. Notably, we calculate that present-day rates of ocean-driven melting in Antarctica4 could be sufficient to initiate retreat of tens to hundreds of metres per day across similar bed settings. This includes regions of the vast and potentially unstable Thwaites Glacier in West Antarctica, which, in the past few years, has retreated to within about 4 km of a flat area of its bed. Although the rates of ice-sheet retreat revealed in this study are much higher than those detected so far by satellites, we note that they do not necessarily represent the upper limit at which retreat can occur. As such, we would not be surprised if similar landforms record even higher rates of retreat in regions that experienced more substantial ice-sheet melting in the past.”); *summarizing* Batchelor C. L., Christie F. D. W., Ottesen D., Montelli A., Evans J., Dowdeswell E. K., Bjarnadóttir L. R., & Dowdeswell J. A. (2023) *Rapid, buoyancy-driven ice-sheet retreat of hundreds of metres per day*, Nature: 1–6.

[197] Fox-Kemper B., *et al.* (2021) *Chapter 9: Ocean, Cryosphere and Sea Level Change*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 1308–1309 , 1302 (“[T]he main uncertainty related to high-end sea-level rise is “when" rather than “if” it arises: the upper limit of 1.02 m of *likely* sea-level range by 2100 for the SSP 5-8.5 scenario will be exceeded in any future warming scenario on time scales of centuries to millennia (*high confidence*), but it is uncertain how quickly the long-term committed sea level will be

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reached (Section 9.6.3.5). Hence, global-mean sea level might rise well above the *likely* range before 2100, which is reflected by assessments of ice-sheet contributions based on structured expert judgment (Bamber et al., 2019) leading to a 95th percentile of projected future sea-level rise as high as 2.3 m in 2100 (Section 9.6.3.3)… High-end sea-level rise can therefore occur if one or two processes related to ice-sheet collapse in Antarctica result in an additional sea-level rise at the maximum of their plausible ranges (Sections 9.4.2.5, 9.6.3.3; Table 9.7) or if several of the processes described in this box result in individual contributions to additional sea-level rise at moderate levels. In both cases, global-mean sea-level rise by 2100 would be substantially higher than the assessed *likely* range, as indicated by the projections including *low confidence* processes reaching in 2100 as high as 1.6 m at the 83rd percentile and 2.3 m at the 95th percentile (Section 9.6.3.3). … While ice-sheet processes in whose projection there is *low confidence* have little influence up to 2100 on projections under SSP1-1.9 and SSP1-2.6 (Table 9.9), this is not the case under higher emissions scenarios, where they could lead to GMSL rise well above the *likely* range. In particular, under SSP5-8.5, *low confidence* processes could lead to a total GMSL rise of 0.6-1.6 m over this time period (17th-83rd percentile range of p-box including SEJ- and MICI-based projections), with 5th-95th percentile projections extending to 0.5-2.3 m (*low confidence*).”). *See also* Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, REV. GEOPHYS. 61: 1–81, 19–20 (“As mentioned above, reduction of the GIS will likely require a millennium. Yet the weakening of ice shelf buttressing directly accelerates ice flow and discharge independent of MISI and MICI processes, with immediate implications for observed rates of sea-level rise. Consequently, under our current best understanding, Greenland and Antarctic ice-sheet collapse cannot be considered an abrupt or fast phenomenon in which most sea level impacts manifest within decades. Nevertheless, ice-sheet losses may contribute to regional sea level rise under RCP8.5 and worst-case scenarios that reaches 1–2 m for many cities globally by 2100, seriously threatening existing communities and infrastructure (Trisos et al., 2022). Over longer timescales, sustained high rates of global sea-level rise (>1 cm/yr by 2200, with further acceleration to up to a couple centimeters per year beyond) may broadly strain coastal adaptation efforts (Oppenheimer et al., 2019). At the same time, models indicate that strong climate mitigation may avert significant fractions of potential sea-level rise and prevent ice-sheet collapse across large regions. In several modeling studies the RCP2.6 scenario prevents collapse of the WAIS (Bulthuis et al., 2019; DeConto & Pollard, 2016) and may reduce the Antarctic contribution to global sea level rise by 2100 to 13 cm (Edwards et al., 2021). … Although significant uncertainties remain regarding the precise temperature thresholds that could trigger ice-sheet collapse, research to date suggests that aggressive climate mitigation could limit risks from ice-sheet instabilities (Table 4).”).

[198] Boers N. & Rypdal M. (2021) *Critical slowing down suggests that the western Greenland Ice Sheet is close to a tipping point*, PROC. NAT’L. ACAD. SCI. 118(21): 1–7, 1 (“A crucial nonlinear mechanism for the existence of this tipping point is the positive melt-elevation feedback: Melting reduces ice sheet height, exposing the ice sheet surface to warmer temperatures, which further accelerates melting. We reveal early-warning signals for a forthcoming critical transition from ice-core-derived height reconstructions and infer that the western Greenland Ice Sheet has been losing stability in response to rising temperatures. We show that the melt-elevation feedback is likely to be responsible for the observed destabilization. Our results suggest substantially enhanced melting in the near future.”). *See also* Intergovernmental Panel on Climate Change (2023) AR6 SYNTHESIS REPORT: CLIMATE CHANGE 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 42 (“Sea level rise is unavoidable for centuries to millennia due to continuing deep ocean warming and ice sheet melt, and sea levels will remain elevated for thousands of years (*high confidence*).”).

[199] Robinson A., Calov R., & Ganopolski A. (2012) *Multistability and critical thresholds of the Greenland ice sheet*, NAT. CLIM. CHANGE 2(6): 429–432, 429 (“Recent studies have focused on the short-term contribution of the Greenland ice sheet to sea-level rise, yet little is known about its long-term stability. The present best estimate of the threshold in global temperature rise leading to complete melting of the ice sheet is 3.1 ºC (1.9–5.1 ºC, 95% confidence interval) above the preindustrial climate, determined as the temperature for which the modelled surface mass balance of the present-day ice sheet turns negative. Here, using a fully coupled model, we show that this criterion systematically overestimates the temperature threshold and that the Greenland ice sheet is more sensitive to long-term climate change than previously thought. We estimate that the warming threshold leading to a monostable, essentially

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ice-free state is in the range of 0.8–3.2 ºC, with a best estimate of 1.6 ºC. By testing the ice sheet's ability to regrow after partial mass loss, we find that at least one intermediate equilibrium state is possible, though for sufficiently high initial temperature anomalies, total loss of the ice sheet becomes irreversible. Crossing the threshold alone does not imply rapid melting (for temperatures near the threshold, complete melting takes tens of millennia). However, the timescale of melt depends strongly on the magnitude and duration of the temperature overshoot above this critical threshold."). *See also* Overland J., Dunlea E., Box J. E., Corell R., Forsius M., Kattsov V., Olsen M. S., Pawlak J., Reiersen L.-O., & Wang M. (2019) *The urgency of Arctic change*, POLAR SCI. 21: 6–13, 9 ("The summer air temperature "viability threshold" that triggers irreversible wastage of the Greenland ice sheet was previously estimated to be for an annual global temperature increase of 2–5 °C (Gregory and Huybrechts, 2006; Huybrechts et al., 2011). An updated estimate based on a higher resolution simulation that explicitly incorporates albedo and elevation feedbacks suggests a lower loss threshold: 0.8–3.2°C (95% confidence range) (Robinson et al., 2012) with 1.6 °C above pre-industrial conditions as a best estimate. It is likely that the Greenland ice sheet enters a phase of irreversible loss under the RCP 4.5 scenario."); Schleussner C.-F., Lissner T. K., Fischer E. M., Wohland J., Perrette M., Golly A., Rogelj J., Childers K., Schewe J., Frieler K., Menge M., Hare W., & Schaeffer M. (2016) *Differential Climate Impacts for Policy-Relevant Limits to Global Warming: the Case of 1.5ºC and 2ºC*, EARTH SYST. DYNAM. 7(2): 327–351, 342 ("In addition to that, Levermann et al. (2013) report a steep increase in long-term SLR between 1.5°C and 2°C as a result of an increasing risk of crossing a destabilizing threshold for the Greenland ice-sheet (Robinson et al., 2012). The disintegration process that would lead to 5–7m global SLR, however, is projected to happen on the timescale of several millennia."); *and* Kopp R. E., Shwon R. L., Wagner G., & Yuan J. (2016) *Tipping elements and climate–economic shocks: Pathways toward integrated assessment*, EARTH'S FUTURE 4(8): 346–372, 354–355 ("For the Greenland Ice Sheet, for example, feedbacks between ice sheet topography and atmospheric dynamics and between ice area and albedo give rise to multiple stable states [*Ridley et al*., 2009; *Robinson et al*., 2012; *Levermann et al*., 2013]. *Robinson et al*. [2012]'s coupled ice-sheet/regional climate model indicated that, at a temperature of 1ºC above pre-Industrial temperatures, the stable states are at 100%, 60%, and 20% of present ice volume. At 1.6ºC, however, their model produced only one stable configuration, at ~15% of the Greenland ice sheet's present volume; thus, 1.6°C warming would represent a commitment to ~6 m of sea-level rise from the Greenland Ice Sheet. The rate of ice sheet mass loss is, however, limited by the flux at the ice sheet margins [e.g., *Pfeffer et al*., 2008], leading to a disconnect between committed and realized change that could persist for millennia, particularly for levels of warming near the threshold [*Applegate et al*., 2015]."). If warming is limited to 2 °C, Greenland could contribute 5 cm of sea-level rise by 2050 and 13 cm by 2100, but if emissions are unabated and warming rises to 5 °C, Greenland could contribute 6 cm of sea-level rise by 2050 and 23 cm by 2100: *see* Bamber J. L., Oppenheimer M., Kopp R. E., Aspinall W. P., & Cooke R. M. (2019) *Ice sheet contributions to future sea-level rise from structured expert judgment*, PROC. NAT'L. ACAD. SCI. 116(23): 11195–11200, 11197 (Table 1).

[200] Trusel L. D., Das S. B., Osman M. B., Evans M. J., Smith B. E., Fettweis X., McConnell J. R., Noël B. P. Y., & van den Broeke M. R. (2018) *Nonlinear rise in Greenland runoff in response to post-industrial Arctic warming*, NATURE 564: 104–108, 104 ("Our results show a pronounced 250% to 575% increase in melt intensity over the last 20 years, relative to a pre-industrial baseline period (eighteenth century) for cores NU and CWG, respectively (Fig. 2). Furthermore, the most recent decade contained in the cores (2004– 2013) experienced a more sustained and greater magnitude of melt than any other 10-year period in the ice-core records. For GrIS cores, 2012 melt is unambiguously the strongest melt season on record. Both NU and CWG annual ice-core-derived melt records significantly ($P < 0.01$) correlate with one another over their 339 years of overlap, and both also with summer air temperatures from the Ilulissat region (Extended Data Table 2; Methods), relationships that improve after applying a 5-year moving average, probably reflecting the noise inherent to melt records owing to variability in meltwater percolation and refreezing. These empirically derived results revealing coherence between independent melt and temperature records emphasize broad-scale GrIS melt forcing, and suggest that summer warming (see Fig. 2) is an important component of the observed regional melt intensification.").

[201] King M. D., Howat I. M., Candela S. G., Noh M. J., Jeong S., Noël B. P. Y., van den Broeke M. R., Wouters B., & Negrete A. (2020) *Dynamic ice loss from the Greenland Ice Sheet driven by sustained glacier retreat*, COMM. EARTH & ENV'T.: 1–7, 1 ("The Greenland Ice Sheet is losing mass at accelerated rates in the 21st century, making it the largest single contributor to rising sea levels. Faster flow of outlet glaciers has substantially contributed to this loss, with the cause of speedup, and potential for future change, uncertain. Here we combine more than three decades

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of remotely sensed observational products of outlet glacier velocity, elevation, and front position changes over the full ice sheet. We compare decadal variability in discharge and calving front position and find that increased glacier discharge was due almost entirely to the retreat of glacier fronts, rather than inland ice sheet processes, with a remarkably consistent speedup of 4–5% per km of retreat across the ice sheet. We show that widespread retreat between 2000 and 2005 resulted in a step-increase in discharge and a switch to a new dynamic state of sustained mass loss that would persist even under a decline in surface melt.”). When compared to the projections of the IPCC Fifth Assessment Report, the associated sea-level rise from the recent ice sheet melting of both Greenland and Antarctica is most like the upper range projections: *see* Slater T., Hogg A. E., & Mottram R. (2020) *Ice-sheet losses track high-end sea-level rise projections*, Comment, NAT. CLIM. CHANGE 10: 879–881, 881 (“In AR5, the ice-sheet contribution by 2100 is forecast from process-based models simulating changes in ice flow and surface mass balance (SMB) in response to climate warming. Driven by the century-scale increase in temperature forced by representative concentration pathways (RCPs), global mean SLR estimates range from 280–980 mm by 2100 (Fig. 1). Of this, the ice-sheet contribution constitutes 4–420 mm (ref. 3). The spread of these scenarios is uncertain, scenario-dependent and increases rapidly after 2030 (Fig. 1). During 2007–2017, satellite observations show total ice-sheet losses increased the global sea level by 12.3 ± 2.3 mm and track closest to the AR5 upper range (13.7–14.1 mm for all emissions pathways) (Fig. 1). Despite a reduction in ice-sheet losses during 2013–2017 — when atmospheric circulation above Greenland promoted cooler summer conditions and heavy winter snowfall2 — the observed average SLR rate (1.23 ± 0.24 mm per year) is 45% above central predictions (0.85 ± 0.07 mm per year) and closest to the upper range (1.39 ± 0.14 mm per year) (Fig. 2).”). In mid-September 2020, consistent warming over northeast Greenland contributed to a large chunk of a glacier breaking away from the Arctic’s largest remaining ice shelf: *see* Amos J. (14 September 2020) *Climate change: Warmth shatters section of Greenland ice shelf*, BBC NEWS (“A big chunk of ice has broken away from the Arctic's largest remaining ice shelf - 79N, or Nioghalvfjerdsfjorden - in 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.”).

[202] Ramirez R. (30 July 2021) *The amount of Greenland ice that melted on Tuesday could cover Florida in 2 inches of water*, CNN (“Greenland is experiencing its most significant melting event of the year as temperatures in the Arctic surge. The amount of ice that melted on Tuesday alone would be enough to cover the entire state of Florida in two inches of water.”).

[203] Robinson A., Calov R., & Ganopolski A. (2012) *Multistability and critical thresholds of the Greenland ice sheet*, NAT. CLIM. CHANGE 2(6): 429–432, 429 (“Recent studies have focused on the short-term contribution of the Greenland ice sheet to sea-level rise, yet little is known about its long-term stability. The present best estimate of the threshold in global temperature rise leading to complete melting of the ice sheet is 3.1 ºC (1.9–5.1 ºC, 95% confidence interval) above the preindustrial climate, determined as the temperature for which the modelled surface mass balance of the present-day ice sheet turns negative. Here, using a fully coupled model, we show that this criterion systematically overestimates the temperature threshold and that the Greenland ice sheet is more sensitive to long-term climate change than previously thought. We estimate that the warming threshold leading to a monostable, essentially ice-free state is in the range of 0.8–3.2 ºC, with a best estimate of 1.6 ºC. By testing the ice sheet’s ability to regrow after partial mass loss, we find that at least one intermediate equilibrium state is possible, though for sufficiently high initial temperature anomalies, total loss of the ice sheet becomes irreversible. Crossing the threshold alone does not imply rapid melting (for temperatures near the threshold, complete melting takes tens of millennia). However, the timescale of melt depends strongly on the magnitude and duration of the temperature overshoot above this critical threshold.”).

[204] King M. D., Howat I. M., Candela S. G., Noh M. J., Jeong S., Noël B. P. Y., van den Broeke M. R., Wouters B., & Negrete A. (2020) *Dynamic ice loss from the Greenland Ice Sheet driven by sustained glacier retreat*, COMM. EARTH & ENV’T.: 1–7, 1 (“The Greenland Ice Sheet is losing mass at accelerated rates in the 21st century, making it the largest single contributor to rising sea levels. Faster flow of outlet glaciers has substantially contributed to this loss, with the cause of speedup, and potential for future change, uncertain.”).

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[205] National Snow & Ice Data Center (18 August 2021) *Rain at the summit of Greenland*, GREENLAND ICE SHEET TODAY ("On August 14, 2021, rain was observed at the highest point on the Greenland Ice Sheet for several hours, and air temperatures remained above freezing for about nine hours. This was the third time in less than a decade, and the latest date in the year on record, that the National Science Foundation's Summit Station had above-freezing temperatures and wet snow. There is no previous report of rainfall at this location (72.58°N 38.46°W), which reaches 3,216 meters (10,551 feet) in elevation.").

[206] Box J. E., Hubbard A., Bahr D. B., Colgan W. T., Fettweis X., Mankoff K. D., Wehrlé A., Noël B., van den Broeke M. R., Wouters B., Bjørk A. A., & Fausto R. S. (2022) *Greenland ice sheet climate disequilibrium and committed sea-level rise*, NAT. CLIM. CHANGE: 808–816, 808 ("Ice loss from the Greenland ice sheet is one of the largest sources of contemporary sea-level rise (SLR). While process-based models place timescales on Greenland's deglaciation, their confidence is obscured by model shortcomings including imprecise atmospheric and oceanic couplings. Here, we present a complementary approach resolving ice sheet disequilibrium with climate constrained by satellite-derived bare-ice extent, tidewater sector ice flow discharge and surface mass balance data. We find that Greenland ice imbalance with the recent (2000–2019) climate commits at least 274 ± 68 mm [10.8 ± 2.7 in] SLR from $59 \pm 15 \times 103\ \text{km}^2$ ice retreat, equivalent to 3.3 ± 0.9% volume loss, regardless of twenty-first-century climate pathways. This is a result of increasing mass turnover from precipitation, ice flow discharge and meltwater run-off. The high-melt year of 2012 applied in perpetuity yields an ice loss commitment of 782 ± 135 mm [30.8 ± 5.3 in] SLR, serving as an ominous prognosis for Greenland's trajectory through a twenty-first century of warming."), *discussed in* Mooney C. (29 August 2022) *Greenland ice sheet set to raise sea levels by nearly a foot, study finds*, THE WASHINGTON POST; *and* Funes Y. (29 August 2022) *The Greenland Ice Sheet's Terrifying Future*, ATMOS.

[207] Smeed D. A., Josey S. A., Beaulieu C., Johns W. E., Moat B. I., Frajka-Williams E., Rayner D., Meinen C. S., Baringer M. O., Bryden H. L., & McCarthy G. D. (2018) *The North Atlantic Ocean Is in a State of Reduced Overturning*, GEOPHYS. RES. LETT. 45(3): 1527–1533, 1527 ("Using data from an array of instruments that span the Atlantic at 26°N, we show that the AMOC has been in a state of reduced overturning since 2008 as compared to 2004–2008. This change of AMOC state is concurrent with other changes in the North Atlantic such as a northward shift and broadening of the Gulf Stream and altered patterns of heat content and sea surface temperature. These changes resemble the response to a declining AMOC predicted by coupled climate models.").

[208] Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, REV. GEOPHYS. 61: 1–81, 5, 7, 8 ("Model simulations of the abovementioned paleoclimate changes indicate that the AMOC may have transitioned rapidly between different modes during past climates, including potentially bistable behaviors. Driven by the salt-advection feedback (Stommel, 1961), the AMOC could switch between "on" and "off" states under natural perturbations such as deglacial meltwater pulses when the ocean system passes certain tipping points.…The AMOC also may have shifted between different modes during Dansgaard-Oeschger events in response to changes in freshwater forcing, rapidly transitioning to a marginally unstable "warm" mode associated with a northward shift of the deep-water formation site and more intense convection, in contrast to flip-ping between an "on" and "off" state (Ganopolski & Rahmstorf, 2001). Moreover, based on an AMOC stability indicator (de Vries & Weber, 2005; W. Liu & Liu, 2013; Rahmstorf, 1996), analyses of modern observations suggest that the current AMOC resides in a bi-stable regime. The circulation may be at risk of an eventual collapse under future anthropogenic warming, as the possibility of an AMOC collapse could be downplayed currently by most coupled climate models due largely to a ubiquitous model bias toward AMOC stability (W. Liu et al., 2014, 2017). … ("Troublingly, defining particular critical temperature thresholds expected to contribute to committed weakening of the overturning circulation also represents a challenge (Weijer et al., 2019). Hoegh-Guldberg et al. (2018) determined a higher likelihood of more intense weakening for >2°C of warming based on model predictions. Committed loss of the GIS is more likely than not to occur beyond a 2°C warming threshold (Pattyn et al., 2018), with the IPCC expressing *medium confidence* regarding long-term near-complete loss of Greenland ice for sustained warming of 3°C or more (IPCC, 2021). As loss of significant volumes of Greenland ice carries important implications for buoyancy dynamics in deep water formation regions, the IPCC's assessment of a 2°C threshold seems a plausible lower bound above which the risks of significant weakening of the AMOC increase. A recent paper suggests that even small, incremental changes in freshwater forcing

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could drive AMOC collapse if the rate of forcing is sufficiently rapid (Lohmann & Ditlevsen, 2021). However, the current ability of models to accurately represent the AMOC and predict its response to climate change remains low, leaving the proximity of today's AMOC to potential critical thresholds uncertain (Weijer et al., 2019). … Taken together, the possibility that the overturning circulation is currently weakening and may weaken further with continuing warming is sufficiently backed by recent research to justify the degree of past and ongoing attention devoted to this potential tipping element."). *See also* Boers N. (2021) *Observation-based early-warning signals for a collapse of the Atlantic Meridional Overturning Circulation*, Nat. Clim. Change 11(8): 680–688, 687 ("The results presented here hence show that the recently discovered AMOC decline during the last decades is not just a fluctuation related to low-frequency climate variability or a linear response to increasing temperatures. Rather, the presented findings suggest that this decline may be associated with an almost complete loss of stability of the AMOC over the course of the last century, and that the AMOC could be close to a critical transition to its weak circulation mode."); *and* Ritchie P. D. L., Clarke J. J., Cox P. M., & Huntingford C. (2021) *Overshooting tipping point thresholds in a changing climate*, Nature 592(7855): 517–523, 522 ("Our analysis reveals that for many climate tipping points it is possible to cross a threshold temporarily without triggering tipping to a different system state. This finding is particularly relevant for potential slow-onset tipping elements such as ice-sheet melt or collapse of the AMOC. Hence, the point of no return for a slow-onset tipping element is not the threshold but some point beyond the threshold. How far this point is beyond the threshold is determined by three factors: (1) the effective timescale of the system, (2) how fast global warming can be reduced and (3) the level at which warming stabilizes.").

[209] Douville H., *et al*. (2021) *Chapter 8: Water Cycle Changes*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 1055–1210, 1148 ("These patterns of past hydroclimatic change are relevant for future projections because it is *very likely* that AMOC will weaken by 2100 in response to increased greenhouse gas emissions (Weaver et al., 2012; Drijfhout et al., 2015; Bakker et al., 2016; Reintges et al., 2017) (See also Section 9.2.3.1). Furthermore, there is *medium confidence* that the decline in AMOC will not involve an abrupt collapse before 2100 (Section 9.2.3.1)."). *See also* Arias P. A., *et al.* (2021) *Technical Summary*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 73 ("While there is *medium confidence* that the projected decline in the Atlantic Meridional Overturning Circulation (AMOC) (TS.2.4) will not involve an abrupt collapse before 2100, such a collapse might be triggered by an unexpected meltwater influx from the Greenland Ice Sheet. If an AMOC collapse were to occur, it would *very likely* cause abrupt shifts in the weather patterns and water cycle, such as a southward shift in the tropical rain belt, and could result in weakening of the African and Asian monsoons and strengthening of Southern Hemisphere monsoons."); Fox-Kemper B., *et al.* (2021) *Chapter 9: Ocean, Cryosphere and Sea Level Change*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 1211–1261, 1239 ("Both the AR5 (Collins et al., 2013) and the SROCC (Collins et al., 2019) assessed that an abrupt collapse of the AMOC before 2100 was *very unlikely*, but the SROCC added that by 2300 an AMOC collapse was *as likely as not* for high-emission scenarios. The SROCC also assessed that model-bias may considerably affect the sensitivity of the modelled AMOC to freshwater forcing. Tuning towards stability and model biases (Valdes, 2011; Liu et al., 2017; Mecking et al., 2017; Weijer et al., 2019) provides CMIP models a tendency toward unrealistic stability (*medium confidence*). By correcting for existing salinity biases, Liu et al. (2017) demonstrated that AMOC behaviour may change dramatically on centennial to millennial timescales and that the probability of a collapsed state increases. None of the CMIP6 models features an abrupt AMOC collapse in the 21st century, but they neglect meltwater release from the Greenland ice sheet and a recent process study reveals that a collapse of the AMOC can be induced even by small-amplitude changes in freshwater forcing (Lohmann and Ditlevsen, 2021). As a result, we change the assessment of an abrupt collapse before 2100 to *medium confidence* that it will not occur."); *and* Intergovernmental Panel on Climate Change (2023) AR6 Synthesis Report: Climate Change 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 1-85, 43 ("The Atlantic Meridional Overturning Circulation is very likely to weaken over the 21st century for all considered scenarios (*high confidence*), however an abrupt collapse is not expected before 2100 (*medium confidence*). If such a low probability event were to occur, it would very likely cause abrupt shifts in regional weather patterns and water cycle, such as a

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southward shift in the tropical rain belt, and large impacts on ecosystems and human activities."). A recent study that incorporates an analysis of early warning signals estimates that the AMOC's transition to a tipping point could happen as early as 2025 (2025–20295 with a 95% confidence range): *see* Ditlevsen P. & Ditlevsen S. (2023) *Warning of a forthcoming collapse of the Atlantic meridional overturning circulation*, NAT. COMMUN. 14(4254): 1–12, 1, 2 ("When complex systems, such as the overturning circulation, undergo critical transitions by changing a control parameter λ through a critical value λc, a structural change in the dynamics happens. The previously statistically stable state ceases to exist and the system moves to a different statistically stable state. The system undergoes a bifurcation, which for λ sufficiently close to λc can happen in a limited number of ways rather independent from the details in the governing dynamics17. Besides a decline of the AMOC before the critical transition, there are early-warning signals (EWSs), statistical quantities, which also change before the tipping happens. These are critical slowing down (increased autocorrelation) and, from the FluctuationDissipation Theorem, increased variance in the signal18–20. The latter is also termed "loss of resilience", especially in the context of ecological collapse21. The two EWSs are statistical equilibrium concepts. Thus, using them as actual predictors of a forthcoming transition relies on the assumption of quasi-stationary dynamics…. The strategy is to infer the evolution of the AMOC solely on observed changes in mean, variance and autocorrelation. The typical choice of control parameter is the flux of freshwater into the North Atlantic. River runoff, Greenland ice melt and export from the Arctic Ocean are not well constrained28; thus, we do not assume the control parameter known. Boers27 assumes the global mean temperature T to represent the control parameter. Although T has increased since ~1920 (Fig. 1d), the increase is not quite linear with time. All we assume here is that the AMOC is in an equilibrium state prior to a change toward the transition. The simplest uninformed assumption is that the change is sufficiently slow and that the control parameter approaches the (unknown) critical value linearly with time. This assumption is confirmed by a close fit of the estimated model to the observed AMOC fingerprint. Although we make no explicit assumptions, the primary driver of climate change, the logarithm of the atmospheric CO2 concentration, does, in fact, increase close to linearly with time in the industrial period29. Our results are robust without making specific assumptions regarding the driver of the AMOC. In this work, we show that a transition of the AMOC is most likely to occur around 2025-2095 (95% confidence interval).").

[210] Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, REV. GEOPHYS. 61: 1–81, 7 ("However, current coupled climate models exhibit biases in surface ocean climatology that favor greater AMOC stability (W. Liu et al., 2014). A modeling analysis correcting for these biases and assuming a CO_2 doubling approximately between the RCP4.5 and RCP6.0 scenarios produced an AMOC collapse 300 years after the CO_2 perturbation (W. Liu et al., 2017), emphasizing a need to improve model physics to allow for more realistic AMOC predictions. An analysis of Earth system models uncovered one instance in which the AMOC declines in strength and then collapses during the 21st century (Drijfhout et al., 2015)."); *citing* Liu W., Liu Z., & Brady E. C. (2014) *Why is the AMOC Monostable in Coupled General Circulation Models?*, J. CLIM. 27(6): 2427–2443, 2427 ("It is found that the monostable AMOC in the control simulation is altered to a bistable AMOC in the flux-adjustment experiment because a reduction of the surface salinity biases in the tropical and northern North Atlantic leads to a reduction of the bias of freshwater transport in the Atlantic. In particular, the tropical bias associated with the double ITCZ reduces salinity in the upper South Atlantic Ocean and, in turn, the AMOC freshwater export, which tends to overstabilize the AMOC and therefore biases the AMOC from bistable toward monostable state."). *See also* Ditlevsen P. & Ditlevsen S. (2023) *Warning of a forthcoming collapse of the Atlantic meridional overturning circulation*, NAT. COMMUN. 14(4254): 1–12, 1 ("A forthcoming collapse of the Atlantic meridional overturning circulation (AMOC) is a major concern as it is one of the most important tipping elements in Earth's climate system1,2,3. In recent years, model studies and paleoclimatic reconstructions indicate that the strongest abrupt climate fluctuations, the Dansgaard-Oeschger events4, are connected to the bimodal nature of the AMOC5,6. Numerous climate model studies show a hysteresis behavior, where changing a control parameter, typically the freshwater input into the Northern Atlantic, makes the AMOC bifurcate through a set of co-dimension one saddle-node bifurcations7,8,9. State-of-the-art Earth-system models can reproduce such a scenario, but the inter-model spread is large and the critical threshold is poorly constrained10,11. Based on the CMIP5 generation of models, the AR6 IPCC report quotes a collapse in the 21st century to be very unlikely (medium confidence)12. Among CMIP6 models, there is a larger spread in the AMOC response to warming scenarios, thus an increased uncertainty in the assessment of a future collapse13. There are, however, model biases toward overestimated stability of the AMOC, both from tuning to the historic climate record14, poor representation of the deep water formation15, salinity and glacial runoff16."); *and* Rahmstorf S. (24 July 2023)

What is happening in the Atlantic Ocean to the AMOC?, RealClimate (“**But: Standard climate models probably underestimate the risk**. There are two reasons for that. They largely ignore Greenland ice loss and the resulting freshwater input to the northern Atlantic which contributes to weakening the AMOC. And their AMOC is likely too stable. There is a diagnostic for AMOC stability, namely the overturning freshwater transport, which I introduced in a paper in 1996 based on Stommel’s 1961 model. Basically, if the AMOC exports freshwater out of the Atlantic, then an AMOC weakening would lead to a fresher (less salty) Atlantic, which would weaken the AMOC further. Data suggest that the real AMOC exports freshwater, in most models it imports freshwater. This is still the case and was also discussed at the IUGG conference.”).

[211] Ditlevsen P. & Ditlevsen S. (2023) *Warning of a forthcoming collapse of the Atlantic meridional overturning circulation*, Nat. Commun 14(4254): 1–12, 6–7 (“We have provided a robust statistical analysis to quantify the uncertainty in observed EWSs for a forthcoming critical transition. The confidence depends on how rapidly the system is approaching the tipping point. With this, the significance of the observed EWSs for the AMOC has been established. This is a stronger result than just observing a significant trend in the EWS by, say, Kendall’s τ test27,33. Here we calculate when the EWS are significantly above the natural variations. Furthermore, we have provided a method to not only determine whether a critical transition will happen but also an estimate of when it will happen. We predict with high confidence the tipping to happen as soon as mid-century (2025–2095 is a 95% confidence range). These results are under the assumption that the model is approximately correct, and we, of course, cannot rule out that other mechanisms are at play, and thus, the uncertainty is larger. However, we have reduced the analysis to have as few and sound assumptions as possible, and given the importance of the AMOC for the climate system, we ought not to ignore such clear indicators of an imminent collapse.”), *discussed in* Rahmstorf S. (24 July 2023) *What is happening in the Atlantic Ocean to the AMOC?*, RealClimate (“10. There are possible Early Warning Signals (EWS). New methods from nonlinear dynamics search for those warning signals when approaching tipping points in observational data, from cosmology to quantum systems. They use the critical slowing down, increasing variance or increasing autocorrelation in the variability of the system. There is the paper by my PIK colleague Niklas Boers (2021), which used 8 different data series (Figure 6) and concluded there is “strong evidence that the AMOC is indeed approaching a critical, bifurcation-induced transition.” Another study, this time using 312 paleoclimatic proxy data series going back a millennium, is Michel et al. 2022. They argue to have found a “robust estimate, as it is based on sufficiently long observations, that the Atlantic Multidecadal Variability may now be approaching a tipping point after which the Atlantic current system might undergo a critical transition. And today (update!) a third comparable study by Danish colleagues has been published, Ditlevsen & Ditlevsen 2023, which expects the tipping point already around 2050, with a 95% uncertainty range for the years 2025-2095. Individual studies always have weaknesses and limitations, but when several studies with different data and methods point to a tipping point that is already quite close, I think this risk should be taken very seriously. Conclusion: Timing of the critical AMOC transition is still highly uncertain, but increasingly the evidence points to the risk being far greater than 10 % during this century – even rather worrying for the next few decades.”).

[212] Lohmann J. & Ditlevsen P. D. (2021) *Risk of tipping the overturning circulation due to increasing rates of ice melt*, Proc. Nat’l. Acad. Sci. 118(9): 1–6, 1, 4 (“Here we show that rate-induced transitions are indeed a concern for the climate system, by demonstrating explicitly the existence of a rate-induced collapse of the AMOC in a three-dimensional model of the global thermohaline circulation with time-dependent freshwater forcing…. From Fig. 3A it is clear that there is no well-defined critical rate separating tipping from tracking realizations. For T > 150 y all realizations track. For 50 y < T < 150 y there is a mixed pattern with some realizations tipping, some tracking, and others visiting the edge state. While for T < 50 y most realizations tip, this is still not guaranteed, since we find a realization for T = 10 y that evolves toward the edge state. Nevertheless, the probability of tipping increases with the rate, comparable to systems with added noise (28).”). *See also* Ritchie P. D. L., Alkhayuon H., Cox P. M., & Wieczorek S. (2023) *Rate-induced tipping in natural and human systems*, Earth Syst. Dyn. 14(3): 669–683, 676 (“For slow rates of increase in freshwater hosing, the system continually adapts and remains within the changing basin of attraction of the base state so that solutions converge to the final base state (the green trajectory). On the other hand, for sufficiently fast rates of increase in freshwater hosing, the system is unable to adapt and falls outside the changing basin of attraction of the base state, causing solutions to converge to the final alterna- tive state (the red trajectory).”).

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[213] Orihuela-Pinto B., England M. H., & Taschetto A. S. (2022) *Interbasin and interhemispheric impacts of a collapsed Atlantic Overturning Circulation*, NAT. CLIM. CHANG. 12(6): 558–565, 558 ("We find that an AMOC collapse drives a complex rearrangement of the global atmospheric circulation that affects all latitudes, from the tropics to the polar circulation of both hemispheres. We find that changes in the tropical Pacific involve a robust intensification of the Walker circulation, a weakening of the subtropical highs in the Southern Hemisphere and an intensification of the Amundsen Sea Low over west Antarctica."). *See also* Intergovernmental Panel on Climate Change (2023) AR6 SYNTHESIS REPORT: CLIMATE CHANGE 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 43 ("The Atlantic Meridional Overturning Circulation is very likely to weaken over the 21st century for all considered scenarios (*high confidence*), however an abrupt collapse is not expected before 2100 (*medium confidence*). If such a low probability event were to occur, it would very likely cause abrupt shifts in regional weather patterns and water cycle, such as a southward shift in the tropical rain belt, and large impacts on ecosystems and human activities."); *and* Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, REV. GEOPHYS. 61: 1–81, 5, 32–33 ("A slowdown or shutdown of the AMOC system would significantly affect regional and global climate patterns (L. C. Jackson et al., 2015; W. Liu et al., 2020). Paleoclimate evidence and numerical simulations have identified AMOC transitions and/or latitudi-nal shift of deep-water formation sites as potential drivers of multiple large, rapid shifts in past climate, including fast or abrupt changes occurring on timescales as short as a few decades (Alley et al., 2001; Bozbiyik et al., 2011; Brovkin et al., 2021; Clark et al., 2001; Ganopolski & Rahmstorf, 2001; Rahmstorf, 2002). The impacts of past AMOC shifts affected climate globally, significantly altering tropical rainfall patterns and causing heat redis-tribution between the northern and southern hemispheres (S. Li & Liu, 2022; Masson-Delmotte et al., 2013). Changes to the overturning circulation could also affect the ocean's strength as a heat and carbon sink (X. Chen & Tung, 2018; Fontela et al., 2016; Nielsen et al., 2019; Romanou et al., 2017) and heat redistribution (S. Li & Liu, 2022; W. Liu & Fedorov, 2019; X. Ma et al., 2020). … In Heinrich events, for example, large discharges of fresh ice from the Laurentide ice sheet into the North Atlantic are hypothesized to have been associated with slowing of the AMOC and cooling of the entire north-ern hemisphere, resulting in a shift of tropical precipitation maxima southward to dry and weaken the West African and South Asian summer monsoons while enhancing South American monsoon precipitation (Chiang & Bitz, 2005; Deplazes et al., 2013; Schneider et al., 2014; X. Wang et al., 2004). In these sorts of scenarios, monsoons may be responding predictably and even linearly to the abrupt forcing of extratropical climate; synchronous changes in insolation may "pace" or "trigger" these changes (Cheng et al., 2016), but the nonlinear response may originate in midlatitude ocean-atmosphere dynamics. Such scenarios bear important lessons for the possible response of monsoons to abrupt changes in the Greenland or Antarctic ice sheets or the Atlantic Meridional Overturning Circulation.").

[214] Douville H., *et al.* (2021) *Chapter 8: Water Cycle Changes*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 1148–1149 ("As with the paleoclimate events, AMOC collapse results in a southward shift in the ITCZ that is most pronounced in the tropical Atlantic. This could cause drying in the Sahel region (Defrance et al., 2017) as well as Mesoamerica and northern Amazonia (Parsons et al., 2014; Chen et al., 2018c). AMOC collapse also causes the Asian monsoon systems to weaken (Liu et al., 2017b) (Figure 8.27b) counteracting the strengthening expected in response to elevated greenhouse gases (see Section 8.4.2). Europe is projected to experience moderate drying in response to AMOC collapse (Jackson et al., 2015)"), *discussed in* Velasquez-Manoff M. & White J. (3 March 2021) *In the Atlantic Ocean, Subtle Shifts Hint at Dramatic Dangers*, THE NEW YORK TIMES ("The consequences could include faster sea level rise along parts of the Eastern United States and parts of Europe, stronger hurricanes barreling into the Southeastern United States, and perhaps most ominously, reduced rainfall across the Sahel, a semi-arid swath of land running the width of Africa that is already a geopolitical tinderbox.").

[215] Sweet W. V., *et al.* (2022) GLOBAL AND REGIONAL SEA LEVEL RISE SCENARIOS FOR THE UNITED STATES: *UPDATED MEAN PROJECTIONS AND EXTREME WATER LEVEL PROBABILITIES ALONG U.S. COASTLINES*, National Oceanic and Atmospheric Administration Technical Report NOS 01, 40 ("By 2050, moderate HTF frequencies nationally are projected to increase by more than a factor of 10, with about a factor of 5 increase in major HTF frequencies. In short,

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assuming continuation of current trends and summarized at the national level, a flood regime shift is projected by 2050, with moderate HTF occurring a bit more frequently than minor HTF events occur today and major HTF events occurring about as frequently as moderate HTF frequencies occur today").

[216] Li Q., England M. H., Hogg A. M., Rintoul S. R., & Morrison A. K. (2023) *Abyssal ocean overturning slowdown and warming driven by Antarctic meltwater*, NATURE 615(7954): 841–847, 845, 847 ("The strength of the AABW overturning cell and the AMOC is projected to decrease by 42% (10.0 Sv) and 19% (2.8 Sv) by 2050, respectively. Meltwater forcing drives virtually all of the reduction in overturning in the AABW cell (Fig. 3d,e), with seawater ageing along the pathway of AABW outflow (Extended Data Fig. 11). The projected decline of AMOC results in reduced northward ocean heat transport50, leading to a cooling trend in the abyssal Atlantic Ocean (Fig. 2). In contrast, the projected decline of AABW drives a warming trend across the abyssal Southern Ocean (Fig. 2), reminiscent in structure to recently observed bottom water trend. … We have shown that projected increases in Antarctic ice melt are set to drive a substantial slowdown of the lower cell of the global overturning circulation over the coming decades, resulting in large and widespread warming of deep waters and reduced ventilation of the abyssal ocean. In particular, a net slowdown of the abyssal ocean overturning circulation of just over 40% is projected to occur by 2050. These changes in the lower cell would profoundly alter the ocean overturning of heat, fresh water, oxygen, carbon and nutrients, with impacts felt throughout the global ocean for centuries to come.").

[217] National Oceanic and Atmospheric Administration, National Ocean Service (20 January 2023) *What is the Atlantic Meridional Overturning Circulation (AMOC)?* ("The ocean's water is constantly circulated by currents. Tidal currents occur close to shore and are influenced by the sun and moon. Surface currents are influenced by the wind. However, other, much slower currents that occur from the surface to the seafloor are driven by changes in the saltiness and ocean temperature, a process called thermohaline circulation. These currents are carried in a large "global conveyor belt," which includes the AMOC. AMOC stands for Atlantic Meridional Overturning Circulation. The AMOC circulates water from north to south and back in a long cycle within the Atlantic Ocean. This circulation brings warmth to various parts of the globe and also carries nutrients necessary to sustain ocean life. The circulation process begins as warm water near the surface moves toward the poles (such as the Gulf Stream in the North Atlantic), where it cools and forms sea ice. As this ice forms, salt is left behind in the ocean water. Due to the large amount of salt in the water, it becomes denser, sinks down, and is carried southwards in the depths below. Eventually, the water gets pulled back up towards the surface and warms up in a process called upwelling, completing the cycle. The entire circulation cycle of the AMOC, and the global conveyor belt, is quite slow. It takes an estimated 1,000 years for a parcel (any given cubic meter) of water to complete its journey along the belt. Even though the whole process is slow on its own, there is some evidence that the AMOC is slowing down further. NOAA funds research to better understand this potential slowing, as well as to investigate the AMOC's role in coastal sea level changes and its relationship to extreme events. As our climate continues to change, is there a possibility that the AMOC will slow down, or come to a complete stop? While research shows it is weakening over the past century, whether or not it will continue to slow or stop circulating completely remains uncertain. If the AMOC does continue to slow down, however, it could have far-reaching climate impacts. For example, if the planet continues to warm, freshwater from melting ice at the poles would shift the rain belt in South Africa, causing droughts for millions of people. It would also cause sea level rise across the U.S. East Coast.").

[218] Scambos T. & Weeman K. (13 December 2021) *The Threat from Thwaites: The Retreat of Antarctica's Riskiest Glacier*, Cooperative Institute for Research in Environmental Sciences ("The glacier is the size of Florida or Britain and currently contributes four percent of annual global sea level rise. If it does collapse, global sea levels would rise by several feet—putting millions of people living in coastal cities in danger zones for extreme flooding. 'Thwaites is the widest glacier in the world,' said Ted Scambos, a senior research scientist at the Cooperative Institute for Research in Environmental Sciences (CIRES). 'It's doubled its outflow speed within the last 30 years, and the glacier in its entirety holds enough water to raise sea level by over two feet. And it could lead to even more sea-level rise, up to 10 feet, if it draws the surrounding glaciers with it.'"). *See also* Rignot E., Mouginot J., Scheuchl B., van den Broeke M., van Wessem M. J., & Morlighem M. (2019) *Four decades of Antarctic Ice Sheet mass balance from 1979–2017*, PROC. NAT'L. ACAD. SCI. 116(4): 1095–1103, 1096 (Table 1 gives 65 cm sea-level equivalent (SLE) for Thwaites glacier).

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[219] Morlighem M., *et al.* (2020) *Deep glacial troughs and stabilizing ridges unveiled beneath the margins of the Antarctic ice sheet*, NAT. GEOSCI. 13: 132–137, 134 ("We do not find major bumps in bed topography upstream of the current grounding line that could stop the grounding line retreat, except for two prominent ridges ~35 and 50 km upstream (red lines, Fig. 2a). Ice sheet numerical models indicate that once the glacier retreats past the second ridge, the retreat of Thwaites Glacier would become unstoppable[18,19,20]."). *See also* Gilbert E. (3 January 2022) *What Antarctica's 'Doomsday' Glacier Could Mean For The World*, SCIENCE ALERT.

[220] Graham A. G. C., Wåhlin A., Hogan K. A., Nitsche F. O., Heywood K. J., Totten R. L., Smith J. A., Hillenbrand C.-D., Simkins L. M., Anderson J. B., Wellner J. S., & Larter R. D. (2022) *Rapid retreat of Thwaites Glacier in the pre-satellite era*, NAT. GEOSCI. 15: 706–713, 706 ("Understanding the recent history of Thwaites Glacier, and the processes controlling its ongoing retreat, is key to projecting Antarctic contributions to future sea-level rise. Of particular concern is how the glacier grounding zone might evolve over coming decades where it is stabilized by sea-floor bathymetric highs. Here we use geophysical data from an autonomous underwater vehicle deployed at the Thwaites Glacier ice front, to document the ocean-floor imprint of past retreat from a sea-bed promontory. We show patterns of back-stepping sedimentary ridges formed daily by a mechanism of tidal lifting and settling at the grounding line at a time when Thwaites Glacier was more advanced than it is today. Over a duration of 5.5 months, Thwaites grounding zone retreated at a rate of >2.1 km per year—twice the rate observed by satellite at the fastest retreating part of the grounding zone between 2011 and 2019. Our results suggest that sustained pulses of rapid retreat have occurred at Thwaites Glacier in the past two centuries. Similar rapid retreat pulses are likely to occur in the near future when the grounding zone migrates back off stabilizing high points on the sea floor."), *discussed in* University of South Florida (5 September 2022) *Faster in the Past: New seafloor images of West Antarctic Ice Sheet upend understanding of Thwaites Glacier retreat*, SCIENCEDAILY.

[221] Morlighem M., *et al.* (2020) *Deep glacial troughs and stabilizing ridges unveiled beneath the margins of the Antarctic ice sheet*, NAT. GEOSCI. 13: 132–137, *discussed in* International Thwaites Glacier Collaboration, *Thwaites Glacier Facts* (*last visited* 14 February 2023) ("**7. Thwaites Glacier ice loss currently contributes around 4% of all global sea-level rise** (assuming 3.5 mm annual sea-level rise) and has the potential to contribute significantly more.").

[222] Groh A., & Horwath M. (2021) *Antarctic Ice Mass Change Products from GRACE/GRACE-FO Using Tailored Sensitivity Kernels*, REMOTE SENS. 13(9): 1736, 1–25, *discussed in* International Thwaites Glacier Collaboration, *Thwaites Glacier Facts* (*last visited* 13 June 2023) ("**10. Since 2000, the glacier has had a net loss of more than 1000 billion tons of ice.** … **11. The amount of ice loss has doubled over the last 30 years** by Thwaites and its neighbouring glaciers.").

[223] Witze A. (11 January 2022) *Giant cracks push imperilled Antarctic glacier closer to collapse*, NATURE NEWS ("The fractures are propagating through the ice at speeds of several kilometres per year. They are heading into weaker and thinner ice, where they could accelerate and lead to the demise of this part of the ice shelf within five years, Pettit estimates."). *See also* Gilbert E. (3 January 2022) *What Antarctica's 'Doomsday' Glacier Could Mean For The World*, SCIENCE ALERT ("But scientists have just confirmed that this ice shelf is becoming rapidly destabilized. The eastern ice shelf now has cracks crisscrossing its surface and could collapse within ten years, according to Erin Pettit, a glaciologist at Oregon State University. This work supports research published in 2020 which also noted the development of cracks and crevasses on the Thwaites ice shelf. These indicate that it is being structurally weakened. This damage can have a reinforcing feedback effect because cracking and fracturing can promote further weakening, priming the ice shelf for disintegration."); Scambos T. & Weeman K. (13 December 2021, *updated* 31 January 2022) *The Threat from Thwaites: The Retreat of Antarctica's Riskiest Glacier*, Cooperative Institute for Research in Environmental Sciences ("Thwaites sits in West Antarctica, flowing across a 120km stretch of frozen coastline. A third of the glacier, along its eastern side, flows more slowly than the rest—it's braced by a floating ice shelf, a floating extension of the glacier that is held in place by an underwater mountain. The ice shelf acts like a brace that prevents faster flow of the upstream ice. But the brace of ice slowing Thwaites won't last for long, said Erin Petitt, an associate professor at Oregon State University. Beneath the surface, warmer ocean water circulating beneath the floating eastern side is attacking this glacier from all angles, her team has found. This water is melting the ice directly from beneath, and as it does so, the glacier loses its grip on the underwater mountain. Massive factures have formed and are growing

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as well, accelerating its demise, said Pettit. This floating extension of the Thwaites Glacier will likely survive only a few more years. … The "chain reaction," beginning with the potential collapse of Thwaites' Eastern Ice Shelf would set in motion a long-term process which would eventually result in global sea level rise. While the initial steps of ice shelf collapse, glacier speed-up, and increased ice-cliff failure might happen within a couple of decades, the "2 to 10 feet" of sea level rise will require centuries to unfold—and impacts can still be mitigated depending on how humans respond in coming decades. Risk of multiple feet of sea level rise will not happen this decade (and likely not even in the next few decades)."); *and* Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, REV. GEOPHYS. 6: 1–81, 16 ("The observational record has established the predominant role of ocean-driven subsurface melt at the base of ice shelves, leading to the thinning and retreat of Antarctic ice shelves (Khazendar et al., 2016; Y. Liu et al., 2015; Wouters et al., 2015). Shifts in atmospheric circulation have driven increased intrusions of warm Circumpolar Deep Water (CDW) onto the continental shelf at depths of several hundred meters, promoting the melt of basal ice (Jenkins et al., 2016). As ice shelves also provide a supportive "buttressing" effect that opposes and slows the rate of ice flux to sea, loss of ice shelf mass itself accelerates flow from ice streams and enhances discharge of ice into the ocean (Schoof, 2007). Ocean warming in combination with physical stresses can also drive an ice shelf damage feedback in which crevasses and fractures develop within the ice shelves buttressing outlet glaciers of the AIS, accelerating ice loss and further exacerbating damage (Lhermitte et al., 2020). Patterns of ice loss have been influenced partly by natural tropical variability (Jenkins et al., 2016) but are also driven by anthropogenically forced shifts in regional winds and positive feedbacks from the ungrounding of ice sheets (P. R. Holland et al., 2019).").

[224] Nilsson J., Gardner A. S., & Paolo F. S. (2022) *Elevation change of the Antarctic Ice Sheet: 1985 to 2020*, EARTH SYST. SCI. DATA. 14(8): 3573–3598, 3573 ("On decadal timescales we find that the large glaciers systems of Pine Island, Thwaites, Smith, and Kohler (basins 21 and 22) have shown relatively stable mass loss since the early parts of the satellite era, with signs of accelerated thinning since 2007–2009 (Fig. 11)."), *discussed in* Jet Propulsion Laboratory (5 September 2022) *Previously Unknown Loss of Antarctic Ice Discovered by NASA – "Antarctica Is Crumbling at Its Edges"*, SCITECHDAILY.

[225] Greene C. A., Gardner A. S., Schlegel N. J., & Fraser A. D. (2022) *Antarctic calving loss rivals ice-shelf thinning*, NATURE 609: 948–953, 948 ("Our model results show that among all of the ice shelves in Antarctica, Pine Island and Thwaites have responded the most strongly to reduced buttressing caused by ice-shelf thinning and calving….We know that ice-shelf thinning tends to occur slowly over time, and can only impact buttressing within a limited range on decadal timescales. By comparison, calving and ice-shelf collapse can occur suddenly, with little warning, and can produce immediate increases in grounding-line flux and sea-level rise."), *discussed in* Jet Propulsion Laboratory (5 September 2022) *Previously Unknown Loss of Antarctic Ice Discovered by NASA – "Antarctica Is Crumbling at Its Edges"*, SCITECHDAILY ("Because losses from calving have outpaced natural ice-shelf growth so greatly, the researchers think it's unlikely Antarctica can grow back to its pre-2000 extent by the end of this century. In fact, the findings suggest that greater losses can be expected: All of Antarctica's largest ice shelves appear to be headed for major calving events in the next 10 to 20 years.").

[226] Cheng L., Abraham J., Hausfather Z., & Trenberth K. E. (2019) *How fast are the oceans warming?*, SCIENCE 363(6423): 128–129, 128 ("About 93% of the energy imbalance accumulates in the ocean as increased ocean heat content (OHC)."). *See also* Intergovernmental Panel on Climate Change (2023) AR6 SYNTHESIS REPORT: CLIMATE CHANGE 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 11 ("It is virtually certain that the global upper ocean (0-700m) has warmed since the 1970s and extremely likely that human influence is the main driver. Ocean warming accounted for 91% of the heating in the climate system, with land warming, ice loss and atmospheric warming accounting for about 5%, 3% and 1%, respectively (*high confidence*)."); von Schuckmann K., *et. al.* (2023) *Heat stored in the Earth system 1960–2020: where does the energy go?*, EARTH SYST. SCI. DATA 15(4): 1675–1709, 1677 ("Here we show that the Earth system has continued to accumulate heat, with 381±61 ZJ accumulated from 1971 to 2020. This is equivalent to a heating rate (i.e., the EEI) of 0.48±0.1 W m^{-2}. The majority, about 89 %, of this heat is stored in the ocean, followed by about 6 % on land, 1 % in the atmosphere,

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and about 4 % available for melting the cryosphere. Over the most recent period (2006–2020), the EEI amounts to 0.76±0.2 W m^{-2}. The Earth energy imbalance is the most fundamental global climate indicator that the scientific community and the public can use as the measure of how well the world is doing in the task of bringing anthropogenic climate change under control. Moreover, this indicator is highly complementary to other established ones like global mean surface temperature as it represents a robust measure of the rate of climate change and its future commitment.").

[227] Solomon S., Daniel J. S., Sanford T. J., Murphy D. M., Plattner G.-K., Knutti R., & Friedlingstein P. (2010) *Persistence of climate changes due to a range of greenhouse gases*, PROC. NAT'L. ACAD. SCI. 107(43): 18354–18359, 18357 ("In the case of a gas with a 10-y lifetime, for example, energy is slowly stored in the ocean during the period when concentrations are elevated, and this energy is returned to the atmosphere from the ocean after emissions cease and radiative forcing decays, keeping atmospheric temperatures somewhat elevated for several decades. Elevated temperatures last longer for a gas with a 100-y lifetime because, in this case, radiative forcing and accompanying further ocean heat uptake continue long after emissions cease. As radiative forcing decays further, the energy is ultimately restored from the ocean to the atmosphere. Fig. 3 shows that the slow timescale of ocean heat uptake has two important effects. It limits the transfer of energy to the ocean if emissions and radiative forcing occur only for a few decades or a century. However, it also implies that any energy that is added to the ocean remains available to be transferred back to the atmosphere for centuries after cessation of emissions."). *See also* MacDougall A. H., *et al.* (2020) *Is there warming in the pipeline? A multi-model analysis of the Zero Emissions Commitment from CO_2*, BIOGEOSCI. 17(11): 2987–3016, 3003 ("Overall, the most likely value of ZEC on decadal timescales is assessed to be close to zero, consistent with prior work. However, substantial continued warming for decades or centuries following cessation of emissions is a feature of a minority of the assessed models and thus cannot be ruled out purely on the basis of models."); Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, REV. GEOPHYS. 61: 1–81, 55 (Figure 16); *and* Intergovernmental Panel on Climate Change (2023) AR6 SYNTHESIS REPORT: CLIMATE CHANGE 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 42 ("Sea level rise is unavoidable for centuries to millennia due to continuing deep ocean warming and ice sheet melt, and sea levels will remain elevated for thousands of years (*high confidence*).").

[228] Cheng L., Foster G., Hausfather Z., Trenberth K. E., & Abraham J. (2022) *Improved Quantification of the Rate of Ocean Warming*, J. CLIM. 35(14): 4827–4840, 4836 ("A robust increase of ocean warming for the upper 2000 m has occurred since 1958 from about 0 to 0.06 ± 0.08 W m^{-2} for 1958–73 to 0.58 ± 0.08 W m^{-2} in 2003–18. With the new methods, the rates of OHC change and EEI since 1958 have been recalculated and updated. The total ocean warming for the upper 2000 m is 341.3 ± 21.0 ZJ from 1958 to 2020 (with the 95% confidence interval). The new estimate suggests a dramatic increase of ocean heat uptake and EEI from 1980s to early 2000s. For the most recent period with better data quality (2005–19) and another estimate of land–ice–atmosphere heat content (Trenberth 2022), the EEI is estimated to 153.9 ZJ (10.99 ZJ yr^{-1}) with the ocean heat uptake of 139.7 ZJ (9.98 ZJ yr^{-1}) for 2005–19. This estimate is slightly lower than that using von Schuckmann et al. (2020) in Fig. 8, indicating uncertainty in land–ice–atmosphere heat content.").

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

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[230] Arias P. A., *et al.* (2021) *Technical Summary*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 74 ("It is *virtually certain* that the global ocean has warmed since at least 1971, representing about 90% of the increase in the global energy inventory (TS.3.1). The ocean is currently warming faster than at any other time since at least the last deglacial transition (*medium confidence*), with warming extending to depths well below 2000 m (*very high confidence*). It is *extremely likely* that human influence was the main driver of ocean warming. Ocean warming will continue over the 21st century (*virtually certain*), and will *likely* continue until at least to 2300 even for low CO_2 emissions scenarios. Ocean warming is irreversible over centuries to millennia (*medium confidence*), but the magnitude of warming is scenario-dependent from about the mid-21st century (*medium confidence*) … Global mean SST has increased since the beginning of the 20th century by 0.88 [0.68 to 1.01] °C, and it is *virtually certain* it will continue to increase throughout the 21st century with increasing hazards to marine ecosystems (*medium confidence*). Marine heatwaves have become more frequent over the 20th century (*high confidence*), approximately doubling in frequency (*high confidence*) and becoming more intense and longer since the 1980s (*medium confidence*).").

[231] Dreyfus G. B., Xu Y., Shindell D. T., Zaelke D., & Ramanathan V. (2022) *Mitigating climate disruption in time: A self-consistent approach for avoiding both near-term and long-term global warming*, Proc. Nat'l. Acad. Sci. 119(22): 1–8, 1 ("We find that mitigation measures that target only decarbonization are essential for strong long-term cooling but can result in weak near-term warming (due to unmasking the cooling effect of co-emitted aerosols) and lead to temperatures exceeding 2°C before 2050. In contrast, pairing decarbonization with additional mitigation measures targeting short-lived climate pollutants (SLCPs) and N_2O, slows the rate of warming a decade or two earlier than decarbonization alone and avoids the 2°C threshold altogether. These non-CO_2 targeted measures when combined with decarbonization can provide net cooling by 2030, reduce the rate of warming from 2030 to 2050 by about 50%, roughly half of which comes from methane, significantly larger than decarbonization alone over this timeframe."). *See also* Intergovernmental Panel on Climate Change (2022) *Summary for Policymakers*, *in* Climate Change 2022: Mitigation of Climate Change, *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Shukla P. R., Skea J., Slade R., Al Khourdajie A., van Diemen R., McCollum D., Pathak M., Some S., Vyas P., Fradera R., Belkacemi M., Hasija A., Lisboa G., Luz S., & Malley J. (eds.), 24 ("In modelled global low emission pathways, the projected reduction of cooling and warming aerosol emissions over time leads to net warming in the near- to mid-term. In these mitigation pathways, the projected reductions of cooling aerosols are mostly due to reduced fossil fuel combustion that was not equipped with effective air pollution controls."); Szopa S., Naik V., Adhikary B., Artaxo P., Berntsen T., Collins W. D., Fuzzi S., Gallardo L., Kiendler-Scharr A., Klimont Z., Liao H., Unger N., & Zanis P. (2021) *Chapter 6: Short-lived climate forcers*, in Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 8822 ("Additional CH_4 and BC mitigation would contribute to offsetting the additional warming associated with SO_2 reductions that would accompany decarbonization (*high confidence*)."); Ramanathan V. & Feng Y. (2008) *On avoiding dangerous anthropogenic interference with the climate system: Formidable challenges ahead*, Proc. Nat'l. Acad. Sci. 105(38): 14245–14250, 14248 ("Switching from coal to ''cleaner'' natural gas will reduce CO_2 emission and thus would be effective in minimizing future increases in the committed warming. However, because it also reduces air pollution and thus the ABC [Atmospheric Brown Cloud] masking effect, it may speed up the approach to the committed warming of 2.4°C (1.4–4.3°C)."); *and* United Nations Environment Programme & World Meteorological Organization (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone, 254 ("Evaluating global mean temperature change, it was found that the targeted measures to reduce emissions of methane and BC could greatly reduce warming rates over the next few decades (Figure 6.1; Box 6.1). When all measures are fully implemented, warming during the 2030s relative to the present would be only half as much as in the reference scenario. In contrast, even a fairly aggressive strategy to reduce CO_2 emissions, as for the CO_2-measures scenario, does little to mitigate warming until after the next 20-30 years (Box 6.2). In fact, sulphur dioxide (SO_2) is coemitted with CO_2 in some of the most highly emitting activities, coal burning in large-scale combustion such as in power plants, for example, that are obvious targets for reduced usage under a CO_2-emissions mitigation strategy. Hence such strategies can lead to additional near-term warming (Figure 6.1), in a well-known temporary effect (e.g. Raes and Seinfeld, 2009), although most of the nearterm warming is driven by CO_2 emissions in the past. The CO_2-measures scenario clearly leads to long-term benefits however, with a dramatically lower warming rate at 2070 under that scenario than

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under the scenario with only CH_4 and BC measures (see Figure 6.1 and timescales in Box 6.2). Hence the near-term measures clearly cannot be substituted for measures to reduce emissions of long-lived GHGs. The near-term measures largely target different source sectors for emissions than the CO_2 measures, so that the emissions reductions of the short-lived pollutants are almost identical regardless of whether the CO_2 measures are implemented or not, as shown in Chapter 5. The near-term measures and the CO_2 measures also impact climate change over different timescales owing to the different lifetimes of these substances. In essence, the near-term CH_4 and BC measures are effectively uncoupled from CO_2 measures examined here.").

[232] Climate scientist and IPCC author Joeri Rogelj, *as quoted in* Berwyn B. (15 September 2021) *The Rate of Global Warming During Next 25 Years Could Be Double What it Was in the Previous 50, a Renowned Climate Scientist Warns*, INSIDE CLIMATE NEWS ("James Hansen, a climate scientist who shook Washington when he told Congress 33 years ago that human emissions of greenhouse gases were cooking the planet, is now warning that he expects the rate of global warming to double in the next 20 years. While still warning that it is carbon dioxide and methane that are driving global warming, Hansen said that, in this case, warming is being accelerated by the decline of other industrial pollutants that they've cleaned from it…. In Hansen's latest warning, he said scientists are dangerously underestimating the climate impact of reducing sulfate aerosol pollution. 'Something is going on in addition to greenhouse warming,' Hansen wrote, noting that July's average global temperature soared to its second-highest reading on record even though the Pacific Ocean is in a cooling La Niña phase that temporarily dampens signs of warming. Between now and 2040, he wrote that he expects the climate's rate of warming to double in an 'acceleration that can be traced to aerosols.' That acceleration could lead to total warming of 2 degrees Celsius by 2040, the upper limit of the temperature range that countries in the Paris accord agreed was needed to prevent disastrous impacts from climate change. What's more, Hansen and other researchers said the processes leading to the acceleration are not adequately measured, and some of the tools needed to gauge them aren't even in place…. A doubling of the rate of global warming would put the planet in the fast lane of glacial melting, sea level rise and coral reef ecosystem die-offs, as well as escalating heatwaves, droughts and floods. But that future is not yet set in stone, said Michael Mann, a climate scientist at Penn State. He said Hansen's prediction appears inconsistent with the scientific literature assessed by the Intergovernmental Panel on Climate Change. The IPCC's latest report advises "that reductions of carbon emissions by 50 percent over the next decade and net-zero by 2100, along with a ramp-down in both aerosols and other short-term agents, including black carbon and other trace anthropogenic greenhouse gases, stabilizes warming well below 2 degrees Celsius," Mann said. But the IPCC report also highlighted that declining aerosol pollution will speed warming. "The removal of air pollution, either through air quality measures or because combustion processes are phased out to get rid of CO2, will result in an increase in the resulting rate of warming," said climate scientist and IPCC report author Joeri Rogelj, director of research at the Imperial College London's Grantham Institute. There's a fix for at least some of this short-term increase in the rate of warming, he said. "The only measures that can counteract this increased rate of warming over the next decades are methane reductions," Rogelj said. "I just want to highlight that methane reductions have always been part of the portfolio of greenhouse gas emissions reductions that are necessary to meet the goals of the Paris Agreement. This new evidence only further emphasizes this need.").

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

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

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

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

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

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

[238] Xu Y. & Ramanathan V. (2017) *Well below 2 °C: Mitigation strategies for avoiding dangerous to catastrophic climate changes*, PROC. NAT'L. ACAD. SCI. 114(39): 10315–10323, 10320, Table S1 ("Hence, the CO_2 measures implemented in 2020 will unmask some of the aerosol cooling (red lines in SI Appendix, Fig. S5) and offset the warming reduction by CO_2 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, CO_2 mitigation is implemented starting from 2020 and CO_2 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 CO_2 emissions beginning in 2020 (CN2020) mitigation scenario (SI Appendix, Fig. S5B vs. S7)."; Table S1 [graph depicting warming potential based on cumulative emissions from CO_2 only, aerosols only, and short-lived climate pollutants only from the 1970's into the 2090's]). *See also* Xu Y. (2020, personal communication). The baseline-fast warming scenario against which these mitigation scenarios are compared includes "unmasking" as emissions of cooling aerosols are reduced in the baseline-fast (RCP6.0) scenarios. If these aerosol emissions continued at current emission levels, undesired from air quality perspective, the warming in 2100 would be 0.6°C smaller.

[239] Xu Y. & Ramanathan V. (2017) *Well below 2 ºC: Mitigation strategies for avoiding dangerous to catastrophic climate changes*, PROC. NAT'L. ACAD. SCI. 114(39): 10315–10323, Supplemental Information, 1 ("In the Baseline-default scenario for CO_2, 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 CO_2 (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 CO_2 (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).").

[240] Xu Y. & Ramanathan V. (2017) *Well below 2 ºC: Mitigation strategies for avoiding dangerous to catastrophic climate changes*, PROC. NAT'L. ACAD. SCI. 114(39): 10315–10323, Supplemental Information, 1 ("In the Baseline-default scenario for CO_2, 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 CO_2 (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 CO_2 (i.e. INDCs and post-2030 decarbonization), emissions effectively increase at a rate of 0.8%/year before 2030 (following INDCs) and then decrease at a rate of 5.5%/year after 2030 (CN2030 in Fig. S2a). The CN2020 scenario is the same as CN2030, except that the peak of emission is reached at 2020 (Fig. S2b)."). *See also Id.* Supplemental Information, 7 (Table S1. The contribution of individual mitigation measures to the warming in the 21st century.).

[241] Shindell D. & Smith C. J. (2019) *Climate and air-quality benefits of a realistic phase-out of fossil fuels*, NATURE 573: 408–411, 409–410, Addendum "Methods" ("These results differ greatly from the idealized picture of a near-instantaneous response to the removal of aerosol cooling followed by a slow transition to dominance by the effects of CO_2. In these more plausible cases, the temperature effects of the reduction in CO_2, SO_2 and CH_4 roughly balance one another until about 2035. After this, the cooling effects of reduced CO_2 continue to increase, whereas the warming induced by a reduction in SO_2 and the cooling induced by the reduction in CH_4 taper off, such that the cooling induced by the reduction in CO_2 dominates (Fig. 3). Examining the effects of CO_2 and SO_2 alone (Fig. 3d), the faster response of SO_2 to the changes in emissions means that the net effect of these two pollutants would indeed be a short-term warming—but a very small one, of between 0.02 °C and 0.10 °C in the ensemble mean temperature response (up to 0.30 °C for the 95th percentile across pathways). Accounting for all fossil-related emissions (Fig. 3e), any brief climate penalty decreases to no more than 0.05 °C (0.19 °C at the 95th percentile), with the smaller value largely due to the additional near-term cooling from reductions in methane. Nearly all the warming in the 2020s and 2030s (Fig. 2) is therefore attributable to the effect of the residual emissions (mainly of CO_2) during the gradual fossil phase-out, as well as the response to historical emissions. … We note that, although this study focuses on the effects of fossil-fuel related emissions, accounting for the effects of reductions in greenhouse gases from non-fossil sources—including

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fluorinated gases and both methane and nitrous oxide from agriculture—along with biofuels that are a large source of warming black carbon, could eliminate any near-term penalty entirely. In fact, given that the net effect of the fossil-fuel phase-out on temperature is minimal during the first 20 years (Fig. 3), reducing those other emissions is the only plausible way in which to decrease warming during that period.”). *See also* Lelieveld J., Klingmüller K., Pozzer A., Burnett R. T., Haines A., & Ramanathan V. (2019) *Effects of fossil fuel and total anthropogenic emission removal on public health and climate*, PROC. NAT'L. ACAD. SCI. 116(15): 7192–7197, 7194 (“Some near-term mitigation can be achieved from the simultaneous reduction of short-lived greenhouse gases such as methane (CH_4), O_3, and hydrofluorocarbons (HFCs) (15, 23–25). Fossil-fuel-related CH_4 emissions constitute nearly 20% of the total source, and removing all anthropogenic CH_4 (nearly 60% of the source), in addition to anthropogenic O_3, would limit the near-term warming to 0.36(±0.06) °C. While the current climate forcing of HFCs is still small, it will be critical to prevent increases in the future, as they are potent greenhouse gases (26). Table 1 presents the unavoidable net warming from emission control measures that simultaneously affect aerosols and greenhouse gases, which have many sources in common. SI Appendix, Table S1 lists these results for all countries, including the uncertainty intervals.”)

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

[243] Intergovernmental Panel on Climate Change (2023) *Summary for Policymakers*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 27 (“Strong, rapid and sustained reductions in CH_4 emissions would also limit the warming effect resulting from declining aerosol pollution and would improve air quality. (Figure SPM.10, Table SPM.2)”. *See also* Intergovernmental Panel on Climate Change (2023) AR6 SYNTHESIS REPORT: CLIMATE CHANGE 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 59 (“Mitigation actions will have other sustainable development co-benefits (*high confidence*). Mitigation will improve air quality and human health in the near-term notably because many air pollutants are co-emitted by GHG emitting sectors and because methane emissions leads to surface ozone formation (*high confidence*) The benefits from air quality improvement include prevention of air pollution-related premature deaths, chronic diseases and damages to ecosystems and crops. The economic benefits for human health from air quality improvement arising from mitigation action can be of the same order of magnitude as mitigation costs, and potentially even larger (*medium confidence*). As methane has a short lifetime but is a potent GHG, strong, rapid and sustained reductions in methane emissions can limit near-term warming and improve air quality by reducing global surface ozone (*high confidence*).”).

[244] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS, 21 (“This is because a realistically paced phase-out of fossil fuels, or even a rapid one under aggressive decarbonization, is likely to have minimal net impacts on near-term temperatures due to the removal of co-emitted aerosols (Shindell and Smith 2019). As methane is the most powerful driver of climate change among the short-lived substances (Myhre et al. 2013), mitigation of methane emissions is very likely to be the most powerful lever in reducing near-term warming. This is consistent with other assessments; for example, the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5) showed that methane controls implemented between 2010 and 2030 would lead to a larger reduction in 2040 warming than the difference between RCPs 2.6, 4.5 and 6.0 scenarios. (The noted IPCC AR5-era scenarios are called representative concentration pathways (RCPs, with the numerical value indicating the target radiative forcing in 2100

(Kirtman et al. 2013)).”). *See also* Shindell D. & Smith C. J. (2019) *Climate and air-quality benefits of a realistic phase-out of fossil fuels*, NATURE 573: 408–411, Addendum “Methods” (“We note that, although this study focuses on the effects of fossil-fuel related emissions, accounting for the effects of reductions in greenhouse gases from non-fossil sources—including fluorinated gases and both methane and nitrous oxide from agriculture—along with biofuels that are a large source of warming black carbon, could eliminate any near-term penalty entirely. In fact, given that the net effect of the fossil-fuel phase-out on temperature is minimal during the first 20 years (Fig. 3), reducing those other emissions is the only plausible way in which to decrease warming during that period.”).

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

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

[247] Xu Y. & Ramanathan V. (2017) *Well below 2 °C: Mitigation strategies for avoiding dangerous to catastrophic climate changes*, PROC. NAT’L. ACAD. SCI. 114(39): 10315–10323, 10321 (“The SP [super pollutant] lever targets SLCPs. Reducing SLCP emissions thins the SP blanket within few decades, given the shorter lifetimes of SLCPs (weeks for BC to about 15 years for HFCs). The mitigation potential of the SP lever with a maximum deployment of current technologies … is about 0.6 °C by 2050 and 1.2 °C by 2100 (SI Appendix, Fig. S5B and Table S1).”). *See also* Szopa S., Naik V., Adhikary B., Artaxo P., Berntsen T., Collins W. D., Fuzzi S., Gallardo L., Kiendler-Scharr A., Klimont Z., Liao H., Unger N., & Zanis P. (2021) *Chapter 6: Short-lived climate forcers*, in CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 821 (“Across the SSPs, the collective reduction of CH_4, ozone precursors and HFCs can make a difference of global mean surface air temperature of 0.2 with a very likely range of [0.1–0.4] °C in 2040 and 0.8 with a very likely range of [0.5–1.3] °C at the end of the 21st century (comparing SSP3-7.0 and SSP1-1.9), which is substantial in the context of the Paris Agreement. Sustained methane mitigation, wherever it occurs, stands out as an option that combines near- and long-term gains on surface temperature (*high confidence*) and leads to air quality benefits by reducing surface ozone levels globally (*high confidence*).”).

[248] 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 CH_4 plus BC measures was –0.54 ± 0.05ºC in the climate model. …Roughly half the forcing is relatively evenly distributed (from the CH_4 measures). The other half is highly inhomogeneous, especially the strong BC forcing, which is greatest over bright desert and snow or ice surfaces. Those areas often exhibit the largest warming mitigation, making the regional temperature response to aerosols and ozone quite distinct from the more homogeneous response to well-mixed greenhouse gases.… BC albedo and direct forcings are large in the Himalayas, where there is an especially pronounced response in the Karakoram, and in the Arctic, where the measures reduce projected warming over the next three decades by approximately two thirds and where regional temperature response patterns correspond fairly closely to albedo forcing (for example, they are larger over the Canadian archipelago than the interior and larger over Russia

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

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

[250] Intergovernmental Panel on Climate Change (2022) *Summary for Policymakers*, *in* Climate Change 2022: Mitigation of Climate Change, *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Shukla P. R., Skea J., Slade R., Al Khourdajie A., van Diemen R., McCollum D., Pathak M., Some S., Vyas P., Fradera R., Belkacemi M., Hasija A., Lisboa G., Luz S., & Malley J. (eds.), 17 ("C.1.2 In modelled pathways that limit warming to 2°C (>67%) assuming immediate action, global net CO_2 emissions are reduced compared to modelled 2019 emissions by 27% [11–46%] in 2030 and by 52% [36-70%] in 2040; and global CH_4 emissions are reduced by 24% [9–53%] in 2030 and by 37% [20–60%] in 2040. In pathways that limit warming to 1.5°C (>50%) with no or limited overshoot global net CO_2 emissions are reduced compared to modelled 2019 emissions by 48% [36–69%] in 2030 and by 80% [61-109%] in 2040; and global CH_4 emissions are reduced by 34% [21–57%] in 2030 and 44% [31-63%] in 2040. There are similar reductions of non-CO_2 emissions by 2050 in both types of pathways: CH_4 is reduced by 45% [25–70%]; N_2O is reduced by 20% [-5 – 55%]; and F-Gases are reduced by 85% [20–90%]. [FOOTNOTE 44] Across most modelled pathways, this is the maximum technical

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potential for anthropogenic CH_4 reductions in the underlying models (*high confidence*). Further emissions reductions, as illustrated by the IMP-SP pathway, may be achieved through changes in activity levels and/or technological innovations beyond those represented in the majority of the pathways (*medium confidence*). Higher emissions reductions of CH_4 could further reduce peak warming. (*high confidence*) (Figure SPM.5)").

[251] Allen M. R., Dube O. P., Solecki W., Aragón-Durand F., Cramer W., Humphreys S., Kainuma M., Kala J., Mahowald N., Mulugetta Y., Perez R., Wairiu M., & Zickfeld K. (2018) *Chapter 1: Framing and Context*, *in* GLOBAL WARMING OF 1.5 °C, *Special Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 61 ("If emission reductions do not begin until temperatures are close to the proposed limit, pathways remaining below 1.5°C necessarily involve much faster rates of net CO_2 emission reductions (Figure 1.4, green lines), combined with rapid reductions in non-CO_2 forcing and these pathways also reach 1.5°C earlier. Note that the emissions associated with these schematic temperature pathways may not correspond to feasible emission scenarios, but they do illustrate the fact that the timing of net zero emissions does not in itself determine peak warming: what matters is total cumulative emissions up to that time. Hence every year's delay before initiating emission reductions decreases by approximately two years the remaining time available to reach zero emissions on a pathway still remaining below 1.5°C (Allen and Stocker, 2013; Leach et al., 2018)."). *See also* United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS, 20 ("For the 2015 United Nations (UN) Paris Agreement to succeed, reducing anthropogenic methane in addition to carbon dioxide is paramount. Currently the largest contributor to the departure from an idealized path to the 2°C target used in the IPCC's Fifth Assessment Report is the growth in methane amounts (Figure 1.3). Achieving the more stringent 1.5°C target requires even larger decreases in methane. The IPCC's 2018 Special Report concluded that reaching a sustainable mitigation pathway to 1.5˚ C can only be achieved with deep and simultaneous reductions of carbon dioxide and all non-carbon dioxide climate forcing emissions, including short-lived climate pollutants such as methane.").

[252] Shindell D. T., Borgford-Parnell N., Brauer M., Haines A., Kuylenstierna J. C. I., Leonard S. A., Ramanathan V., Ravishankara A., Amann M., & Srivastava L. (2017) *A climate policy pathway for near- and long-term benefits*, SCIENCE 356(6337): 493–494.

[253] Ripple W. J., Wolf C., Newsome T. M., Barnard P., & Moomaw W. R. (2020) *World Scientists' Warning of a Climate Emergency*, BIOSCI. 70: 8–12.

[254] Ripple W. J., Wolf C., Newsome T. M., Gregg J. W., Lenton T. M., Palomo I., Eikelboom J. A. J., Law B. E., Huq S., Duffy P. B., & Rockström J. (2021) *World Scientists' Warning of a Climate Emergency 2021*, BIOSCI. 71(9): 894–898, 897 ("Given the impacts we are seeing at roughly 1.25 degrees Celsius (°C) warming, combined with the many reinforcing feedback loops and potential tipping points, massive-scale climate action is urgently needed. The remaining carbon budget for 1.5°C was recently estimated to have a 17% chance of being negative, indicating that we may already have lost the opportunity to limit warming to this level without overshoot or risky geoengineering (Matthews et al. 2021). Because of the limited time available, priorities must shift toward immediate and drastic reductions in dangerous short-lived greenhouse gases, especially methane (UNEP/CCAC 2021).").

[255] Parties to the United Nations Framework Convention on Climate Change are required to report emissions on a gas-by-gas basis in units of mass. *See* United Nations Framework Convention on Climate Change, Dec. 18/CMA.1, FCCC/PA/CMA/2018/3/Add.2, at Annex ¶47 (2019) ("47. Each Party shall report estimates of emissions and removals for all categories, gases and carbon pools considered in the GHG inventory throughout the reported period on a gas-by-gas basis in units of mass at the most disaggregated level, in accordance with the IPCC guidelines referred to in paragraph 20 above, using the common reporting tables, including a descriptive summary and figures underlying emission trends, with emissions by sources listed separately from removals by sinks, except in cases where it may be technically impossible to separate information on emissions and removals in the LULUCF sector, and noting that a minimum level of aggregation is needed to protect confidential business and military information."). *See also* Allen M. R., *et al.* (2022) *Indicate separate contributions of long-lived and short-lived greenhouse gases in emission targets*, NPJ CLIM. ATMOS. SCI. 5(5): 1–4, 1 ("As researchers who have published over recent years on the issue of comparing the climate effects of different greenhouse gases, we would like to highlight a simple innovation that would enhance

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the transparency of stocktakes of progress towards achieving any multi-decade-timescale global temperature goal. In addition to specifying targets for total CO_2-equivalent emissions of all greenhouse gases, governments and corporations could also indicate the separate contribution to these totals from greenhouse gases with lifetimes around 100 years or longer, notably CO_2 and nitrous oxide, and the contribution from Short-Lived Climate Forcers (SLCFs), notably methane and some hydrofluorocarbons. This separate indication would support an objective assessment of the implications of aggregated emission targets for global temperature, in alignment with the UNFCCC Parties' Decision (4/CMA.1)1 to provide 'information necessary for clarity, transparency and understanding" in nationally determined contributions (NDCs) and long-term low-emission development strategies (LT-LEDSs).'").

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

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

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

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

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

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

[262] Rogelj J. & Schleussner C.-F. (2021) *Reply to Comment on `Unintentional unfairness when applying new greenhouse gas emissions metrics at country level'*, Environ. Res. Lett. 16(6): 1–8, 2 ("These ethical issues arise from moving away from an emissions centered metric like GWP-100—where every unit of emissions of a certain GHG is treated equally and independent of the emitter or timing of emissions—to metrics like GWP*—which focus on additional warming and where the treatment of a unit of emissions depends on the emitter and their emission history… Meanwhile, a group of the world's biggest diary producers seems happy to consider the grandfathering GWP* perspective and explicitly dismisses other fairness perspectives that would increase their companies' responsibility for reducing methane emissions (Cady 2020)."); *citing* Cady R. (2020) *A Literature Review of GWP*: A proposed method for estimating global warming potential (GWP*) of short-lived climate pollutants like methane*, Global Dairy Platform, *discussed in* Elgin B. (19 October 2021) *Beef Industry Tries to Erase Its Emissions With Fuzzy Methane Math*, Bloomberg Green.

[263] Intergovernmental Panel on Climate Change (2021) *Summary for Policymakers*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), Figure SPM.2.

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

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

[265] United Nations Environment Programme (2021) Emissions Gap Report 2021: The Heat Is On – A World of Climate Promises Not Yet Delivered, 47 (“Over the last two decades, the main cause of increasing atmospheric methane is likely increasing anthropogenic emissions, with hotspot contributions from agriculture and waste in South and South-East Asia, South America and Africa, and from fossil fuels in China, the Russian Federation and the United States of America (Jackson *et al.* 2020). Emissions from natural sources may also be increasing, as wetlands warm, tropical rainfall increases and permafrost thaws.”). *See also* Lan X., Nisbet E. G., Dlugokencky E. J., & Michel S. E. (2021) *What do we know about the global methane budget? Results from four decades of atmospheric* CH_4 *observations and the way forward*, Phil. Trans. R. Soc. A 379(2210): 1–14, 11 (“Explaining the renewed and accelerating increase in atmospheric CH_4 burden since 2007 remains challenging, and the exact causes are not yet clear. But, the observations we describe suggest that increased emissions from microbial sources are the strongest driver, with a relatively smaller contribution from other processes, e.g., fossil fuel exploitation. A more difficult question to answer is the one posed by this special issue: is warming feeding the warming? We cannot say for certain, but we cannot rule out the possibility that climate change is increasing CH_4 emissions. The strong signals from the tropics combined with the isotopic data are consistent with increased emissions from natural wetlands, but large [interannual variability (IAV)] and inter-decadal variability in wetland drivers like precipitation make it difficult to identify small trends. Observations are needed that will help process models capture this variability. The size of the IAV illustrates the potential scope of uncontrollable near-future change and emphasizes the urgency of reducing the global methane burden by mitigating the methane emissions that we can control, from the fossil fuel and agricultural sectors.”); Peng S., Lin X., Thompson R. L., Xi Y., Liu G., Hauglustaine D., Lan X., Poulter B., Ramonet M., Saunois M., Yin Y., Zhang Z., Zheng B., & Ciais P. (2022) *Wetland emission and atmospheric sink changes explain methane growth in 2020*, Nature 612(7940): 477–482, 481 (“In summary, our results show that an increase in wetland emissions, owing to warmer and wetter conditions over wetlands, along with decreased OH, contributed to the soaring methane concentration in 2020. The large positive MGR anomaly in 2020, partly due to wetland and other natural emissions, reminds us that the sensitivity of these emissions to interannual variation in climate has had a key role in the renewed growth of methane in the atmosphere since 2006. The wetland methane–climate feedback is poorly understood, and this study shows a high interannual sensitivity that should provide a benchmark for future coupled CH_4 emissions–climate models. We also show that the decrease in atmospheric CH_4 sinks, which resulted from a reduction of tropospheric OH owing to less NO_x emissions during the lockdowns, contributed 53 ± 10% of the MGR anomaly in 2020 relative to 2019. Therefore, the unprecedentedly high methane growth rate in 2020 was a compound event with both a reduction in the atmospheric CH_4 sink and an increase in Northern Hemisphere natural sources. With emission recovery to pre-pandemic levels in 2021, there could be less reduction in OH. The persistent high MGR anomaly in 2021 hints at mechanisms that differ from those responsible for 2020, and thus awaits an explanation.”); Qu Z., Jacob D. J., Zhang Y., Shen L., Varon D. J., Lu X., Scarpelli T., Bloom A., Worden J., & Parker R. J. (2022) *Attribution of the 2020 surge in atmospheric methane by inverse analysis of GOSAT observations*, Environ. Res. Lett. 17(9): 1–8, 6 (“The inversion shows an increase in the methane growth rate from 28 Tg a−1 in 2019 to 59 Tg a−1 in 2020, consistent with observations. This implies a forcing on the methane budget away from a steady state by 36 Tg a−1 from 2019 to 2020, 86% (82 ± 18% in the nine-member inversion ensemble) of which is from the increase in emissions between the two years and the rest is from the decrease in tropospheric OH. Changes in methane mass offset the forcing by 5 Tg a−1 . The global mean OH concentration decreases by 1.2% (1.6 ± 1.5%) from 2019 to 2020, which could be due to reduced NOx emissions from COVID-19 decreases in economic activity but accounts for only a small fraction of the methane surge. We find that half of the increase in methane emissions from 2019 to 2020 is due to Africa. High precipitation and flooding in East Africa leading to increased wetland methane emissions could explain the increase. We also find a large relative increase in Canadian emissions, also apparently driven by wetlands..”); Rehder Z., Kleinen T., Kutzbach L., Stepanenko V., Langer M., & Brovkin V. (13 January 2023) *Simulated methane emissions from Arctic ponds are highly sensitive to warming*, Biogeosci. Discuss. (*preprint*): 1–30, 2, 21 (“Most Arctic ponds emit predominantly contemporary, recently fixed, carbon (Negandhi et al., 2013; Bouchard et al., 2015; Dean et al., 2020). However, newly-formed ice-wedge ponds might emit older carbon than the average Arctic pond. When the permafrost adjacent to the thawing ice wedge degrades, old carbon can leech from the thawed sediments into the pond fueling methanogenesis (Langer et al., 2015; Preskienis et al., 2021) and exerting a positive climatic feedback. Furthermore, the composition of the ponds’ methanogenic communities might change in

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response to the warming Arctic. … While ponds are not hotspots of methane emissions in our study area under the current climate, our model simulations indicate that they will become stronger methane sources under further warming. We project an increase of pond methane emissions of 1.33 g CH_4 m^{-2} year^{-1} °C^{-1} ."); *and* Kleinen T., Gromov S., Steil B., & Brovkin V. (2021) *Atmospheric methane underestimated in future climate projections*, Environ. Res. Lett. 16(9): 1–14, 4–5 ("In the case of the low radiative forcing scenarios SSP1–1.9 and SSP1–2.6, the concentration maximum occurs at the end of the historical period and does not differ significantly between our experiments and the published scenarios. The concentration decline after that maximum, however, occurs much more slowly in our experiments, leading to higher atmospheric methane concentrations than in the published scenarios. For the moderate to high warming scenarios SSP2–4.5, SSP3–7.0 and SSP5–8.5, however, the evolution of atmospheric methane is much more dramatic. Here, maximum atmospheric concentrations become substantially higher than in the published scenarios and stay at a very high level until the end of the experiments in 3000 CE. For SSP2–4.5, the maximum in CH_4 is 50% higher than published previously, for SSP3–7.0 it is 131% higher and for SSP5–8.5 it is 130% higher.").

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

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

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

[269] United Nations Environment Programme & Climate & Clean Air Coalition (2021) Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions, 17 ("Mitigation of methane is very likely the strategy with the greatest potential to decrease warming over the next 20 years."). *See also* Ross K., Waskow D., & Ge M. (17 September 2021) *How Methane Emissions Contribute to Climate Change*, World Resources Institute ("Methane is the second most abundant human-caused greenhouse gas (GHG), and is 86 times more powerful than carbon dioxide over 20 years in the atmosphere (34 times more powerful over 100 years). Because it exists for a relatively short time in the atmosphere, cutting methane provides a quick benefit in terms of limiting near-term temperature rise. Studies estimate that ambitious actions to reduce methane can avoid 0.3 degrees C of warming by 2050.").; *and* Intergovernmental Panel on Climate Change (2023) AR6 Synthesis Report: Climate Change 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 33, 57 ("Global warming will continue to increase in the near term in nearly all considered scenarios and modelled pathways. Deep, rapid and sustained GHG emissions reductions, reaching net zero CO_2 emissions and including strong emissions reductions of other GHGs, in particular CH_4, are necessary to limit warming to 1.5°C (>50%) or less than 2°C (>67%) by the end

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of century (*high confidence*). … All global modelled pathways that limit warming to 2°C (>67%) or lower by 2100 involve reductions in both net CO_2 emissions and non-CO_2 emissions (see Figure 3.6) (*high confidence*). For example, in pathways that limit warming to 1.5°C (>50%) with no or limited overshoot, global CH_4 (methane) emissions are reduced by 34% [21–57%] below 2019 levels by 2030 and by 44% [31–63%] in 2040 (*high confidence*). Global CH_4 emissions are reduced by 24% [9–53%] below 2019 levels by 2030 and by 37% [20–60%] in 2040 in modelled pathways that limit warming to 2°C with action starting in 2020 (>67%) (*high confidence*). (CrossSection Box.2).").

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

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

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

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

[274] United Nations Environment Programme & Climate & Clean Air Coalition (2021) Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions, 21 ("The short lifetime of methane, and the quick response of methane abundance to reduced emissions described earlier, mean that any action taken to reduce emissions will have an immediate pay off for climate in addition to the current and near-future human health and agricultural production. Observations over the past few decades have shown that decreased emissions lead quickly to lower methane levels relative to those that could be expected in the absence of the decreases. That is, there are no mechanisms that offset the decreases even though there are significant natural sources. Simply put, natural emissions do not make up for the decrease in anthropogenic emission. Indeed, the expectation that a reduction in emissions will yield quick results, in the order of a decade, is confirmed and emphasizes the importance of methane.").

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

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

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

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

[279] Nzotungicimpaye C. M., MacIsaac A. J., & Zickfeld K. (2023) *Delaying methane mitigation increases the risk of breaching the 2 °C warming limit*, COMMUN. EARTH. ENVIRON. 4(250): 1–8, 2–3 ("The timing of CH_4 mitigation affects peak levels of [CH_4], [CO_2], and surface air temperature (SAT) in the future. According to our model, every

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10-year delay in CH_4 mitigation increases the [CH_4] peak by 150-180 ppb (Fig. 2b). As such, delaying CH_4 mitigation to the 2040-2050 decade will increase the [CH_4] peak by 450–540 ppb relative to CH_4 mitigation initiated at or around 2020. The [CH_4] increase has a direct effect on global mean surface air temperature (SAT). For every 10-year delay in CH_4 mitigation, our model simulates an additional peak warming of ~0.1 °C (Fig. 2d). Delaying CH_4 mitigation to or around mid-century will increase the peak warming by 0.2–0.3 °C relative to a CH_4 mitigation initiated at present-day. Through feedback mechanisms operating in the Earth system (discussed below), one indirect effect of delaying CH_4 mitigation manifests with atmospheric CO_2 concentration ([CO_2]). Our model suggests that every 10-year delay in CH_4 mitigation implies an increase in the [CO_2] peak by 2-3 ppm (Fig. 2c). Consequently, delaying CH_4 mitigation to the 2040-2050 decade will increase the [CO_2] peak by 6-9 ppm relative to CH_4 mitigation at present-day. Relative to the early mitigation scenario (SSP1-2.6), delaying CH_4 mitigation to the 2040-2050 decade implies more [CH_4] (~200 ppb) and warming (~0.2 °C) at the year 2100 (Fig. 2b, d and Supplementary Note 3).").

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

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

[282] Intergovernmental Panel on Climate Change (2022) *Summary for Policymakers*, *in* Climate Change 2022: Mitigation of Climate Change, *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Shukla P. R., Skea J., Slade R., Al Khourdajie A., van Diemen R., McCollum D., Pathak M., Some S., Vyas P., Fradera R., Belkacemi M., Hasija A., Lisboa G., Luz S., & Malley J. (eds.), 23, 24 ("Deep GHG emissions reductions by 2030 and 2040, particularly reductions of methane emissions, lower peak warming, reduce the likelihood of overshooting warming limits and lead to less reliance on net negative

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CO2 emissions that reverse warming in the latter half of the century. Reaching and sustaining global net zero GHG emissions results in a gradual decline in warming. (*high confidence*) (Table SPM.1)").

[283] Intergovernmental Panel on Climate Change (2022) *Summary for Policymakers*, *in* Climate Change 2022: Mitigation of Climate Change, *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Shukla P. R., Skea J., Slade R., Al Khourdajie A., van Diemen R., McCollum D., Pathak M., Some S., Vyas P., Fradera R., Belkacemi M., Hasija A., Lisboa G., Luz S., & Malley J. (eds.), 17 ("C.1.2 In modelled pathways that limit warming to 2°C (>67%) assuming immediate action, global net CO$_2$ emissions are reduced compared to modelled 2019 emissions by 27% [11–46%] in 2030 and by 52% [36-70%] in 2040; and global CH$_4$ emissions are reduced by 24% [9–53%] in 2030 and by 37% [20–60%] in 2040. In pathways that limit warming to 1.5°C (>50%) with no or limited overshoot global net CO$_2$ emissions are reduced compared to modelled 2019 emissions by 48% [36–69%] in 2030 and by 80% [61-109%] in 2040; and global CH$_4$ emissions are reduced by 34% [21–57%] in 2030 and 44% [31-63%] in 2040. There are similar reductions of non-CO$_2$ emissions by 2050 in both types of pathways: CH$_4$ is reduced by 45% [25–70%]; N$_2$O is reduced by 20% [-5 – 55%]; and F-Gases are reduced by 85% [20–90%]. [FOOTNOTE 44] Across most modelled pathways, this is the maximum technical potential for anthropogenic CH$_4$ reductions in the underlying models (*high confidence*). Further emissions reductions, as illustrated by the IMP-SP pathway, may be achieved through changes in activity levels and/or technological innovations beyond those represented in the majority of the pathways (*medium confidence*). Higher emissions reductions of CH$_4$ could further reduce peak warming. (*high confidence*) (Figure SPM.5)"). *See also* Intergovernmental Panel on Climate Change (2023) AR6 Synthesis Report: Climate Change 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 57 ("All global modelled pathways that limit warming to 2°C (>67%) or lower by 2100 involve reductions in both net CO$_2$ emissions and non-CO$_2$ emissions (see Figure 3.6) (*high confidence*). For example, in pathways that limit warming to 1.5°C (>50%) with no or limited overshoot, global CH$_4$ (methane) emissions are reduced by 34% [21–57%] below 2019 levels by 2030 and by 44% [31–63%] in 2040 (*high confidence*). Global CH$_4$ emissions are reduced by 24% [9–53%] below 2019 levels by 2030 and by 37% [20–60%] in 2040 in modelled pathways that limit warming to 2°C with action starting in 2020 (>67%) (*high confidence*).").

[284] Saunois M., *et al*. (2020) *The Global Methane Budget* 2000-2017, Earth Syst. Sci. Data 12(3): 1561–1623, 1561 ("For the 2008–2017 decade, global methane emissions are estimated by atmospheric inversions (a top-down approach) to be 576 Tg CH$_4$ yr^{-1} (range 550–594, corresponding to the minimum and maximum estimates of the model ensemble). Of this total, 359 Tg CH$_4$ yr^{-1} or ∼ 60 % is attributed to anthropogenic sources, that is emissions caused by direct human activity (i.e. anthropogenic emissions; range 336–376 Tg CH$_4$ yr^{-1} or 50 %–65 %).").

[285] United Nations Environment Programme & Climate & Clean Air Coalition (2021) Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions, 25 ("Anthropogenic methane emissions come primarily from three sectors: fossil fuels, ~35 per cent; agriculture, ~40 per cent; and waste, ~20 per cent.").

[286] Shindell D. (25 May 2021) *Benefits and Costs of Methane Mitigation*, Presentation at the CCAC Working Group Meeting. *Updating* Figure 3d from Shindell D. & Smith C. J. (2019) *Climate and air-quality benefits of a realistic phase-out of fossil fuels*, Nature 573: 408–411. *See also* United Nations Environment Programme & Climate & Clean Air Coalition (2021) Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions.

[287] Jackson R. B., *et al.* (2020) *Increasing anthropogenic methane emissions arise equally from agricultural and fossil fuel sources*, Environ. Res. Lett. 15(7): 1–7, 6 ("Increased emissions from both the agriculture and waste sector and the fossil fuel sector are likely the dominant cause of this global increase (figures 1 and 4), highlighting the need for stronger mitigation in both areas. Our analysis also highlights emission increases in agriculture, waste, and fossil fuel sectors from southern and southeastern Asia, including China, as well as increases in the fossil fuel sector in the United States (figure 4). In contrast, Europe is the only continent in which methane emissions appear to be decreasing. While changes in the sink of methane from atmospheric or soil uptake remains possible (Turner *et al* 2019), atmospheric

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chemistry and land-surface models suggest the timescales for sink responses are too slow to explain most of the increased methane in the atmosphere in recent years. Climate policies overall, where present for methane mitigation, have yet to alter substantially the global emissions trajectory to date.”).

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

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

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

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

[292] United States Climate Alliance (2018) FROM SLCP CHALLENGE TO ACTION: A ROADMAP FOR REDUCING SHORT-LIVED CLIMATE POLLUTANTS TO MEET THE GOALS OF THE PARIS AGREEMENT, 13 (“Actions to improve manure management and to reduce methane from enteric fermentation have the potential to significantly reduce agricultural methane emissions across U.S. Climate Alliance states. Improving manure storage and handling, composting manure,

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

[293] In the U.S. alone, natural gas stoves emit 28.1 Gg of methane a year, among other climate pollutants that are hazardous to the environment and human health: *see* Lebel E. D., Finnegan C. J., Ouyang Z., & Jackson R. B. (2022) *Methane and NO_x Emissions from Natural Gas Stoves, Cooktops, and Ovens in Residential Homes*, ENVIRON. SCI. TECHNOL. 56(4): 2529–2539, 2529 ("Natural gas stoves in >40 million U.S. residences release methane (CH_4)─a potent greenhouse gas─through post-meter leaks and incomplete combustion. We quantified methane released in 53 homes during all phases of stove use: steady-state-off (appliance not in use), steady-state-on (during combustion), and transitory periods of ignition and extinguishment. We estimated that natural gas stoves emit 0.8–1.3% of the gas they use as unburned methane and that total U.S. stove emissions are 28.1 [95% confidence interval: 18.5, 41.2] Gg CH_4 year^{-1}. More than three-quarters of methane emissions we measured originated during steady-state-off. Using a 20-year timeframe for methane, annual methane emissions from all gas stoves in U.S. homes have a climate impact comparable to the annual carbon dioxide emissions of 500 000 cars. In addition to methane emissions, co-emitted health-damaging air pollutants such as nitrogen oxides (NO_x) are released into home air and can trigger respiratory diseases. In 32 homes, we measured NO_x (NO and NO_2) emissions and found them to be linearly related to the amount of natural gas burned ($r^2 = 0.76$; $p \ll 0.01$). Emissions averaged 21.7 [20.5, 22.9] ng NO_x J^{-1}, comprised of 7.8 [7.1, 8.4] ng NO_2 J^{-1} and 14.0 [12.8, 15.1] ng NO J^{-1}. Our data suggest that families who don't use their range hoods or who have poor ventilation can surpass the 1-h national standard of NO_2 (100 ppb) within a few minutes of stove usage, particularly in smaller kitchens.").

[294] Höglund-Isaksson L., Gómez-Sanabria A., Zbigniew K., Rafaj P., & Schöpp W. (2020) *Technical potentials and costs for reducing global anthropogenic methane emissions in the 2050 timeframe—results from the GAINS model*, ENVIRON. RES. COMM. 2(2): 1–21, 16–17 ("An additional almost 10 percent of baseline emissions in 2050 could be

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removed at a marginal cost below 20 €/t CO$_2$eq by implementing proper waste and wastewater handling in China, India and the rest of South-East Asia. This would likely come with considerable co-benefits in the form of reduced air and water pollution.").

[295] United States Climate Alliance (2018) From SLCP Challenge to Action: A roadmap for reducing short-lived climate pollutants to meet the goals of the Paris Agreement, 15 ("Significant opportunities for reducing methane emissions from landfills and capturing value can be seized by reducing food loss and waste, diverting organic waste to beneficial uses, and improving landfill management. These and other actions collectively could reduce methane emissions from waste by an estimated 40-50 percent by 2030 (Appendix A). Such efforts could add value in our states by reducing emissions of volatile organic compounds and toxic air contaminants from landfills, recovering healthy food for human consumption in food insecure communities, supporting healthy soils and agriculture, generating clean energy and displacing fossil fuel consumption, and providing economic opportunities across these diverse sectors. Many of these benefits will accrue in low-income and disadvantaged communities."). *See also* Geyik Ö., Hadjikakou M., & Bryan B. A. (2022) *Climate-friendly and nutrition-sensitive interventions can close the global dietary nutrient gap while reducing GHG emissions*, Nat. Food. 4: 61–73, 61 ("Here, we estimate the non-CO$_2$ greenhouse gas emissions resulting from closing the world's dietary nutrient gap—that between country-level nutrient supply and population requirements—for energy, protein, iron, zinc, vitamin A, vitamin B12 and folate under five climate-friendly intervention scenarios in 2030. We show that improving crop and livestock productivity and halving food loss and waste can close the nutrient gap with up to 42% lower emissions (3.03 Gt CO$_2$eq yr^{-1}) compared with business-as-usual supply patterns with a persistent nutrient gap (5.48 Gt CO$_2$eq yr^{-1}).").

[296] Jackson R. B., *et al.* (2021) *Atmospheric methane removal: a research agenda*, Philos. Trans. R. Soc. A 379(2210): 1–17, 3–4 ("Atmospheric methane removal may be needed to offset continued methane release and limit the global warming contribution of this potent greenhouse gas. Eliminating most anthropogenic methane emissions is unlikely this century, and sudden methane release from the Arctic or elsewhere cannot be excluded, so technologies for negative emissions of methane may be needed. Carbon dioxide removal (CDR) has a well-established research agenda, technological foundation and comparative modelling framework [23–28]. No such framework exists for methane removal. We outline considerations for such an agenda here. We start by presenting the technological Mt CH$_4$ yr^{-1} considerations for methane removal: energy requirements (§2a), specific proposed technologies (§2b), and air processing and scaling requirements (§2c). We then outline the climate and air quality impacts and feedbacks of methane removal (§3a) and argue for the creation of a Methane Removal Model Intercomparison Project (§3b), a multi-model framework that would better quantify the expected impacts of methane removal. In §4, we discuss some broader implications of methane removal."). *See also* Abernethy S., O'Connor F. M., Jones C. D., & Jackson R. B. (2021) *Methane removal and the proportional reductions in surface temperature and ozone*, Philos. Trans. R. Soc. A 379(2210): 1–13, 6 ("Due to the temporal nature of effective cumulative removal, comparisons between methane and carbon dioxide depend on the timescale of interest. The equivalent of MCR for carbon dioxide, the TCRE, is 0.00048 ± 0.0001°C per Pg CO$_2$ [38], two orders of magnitude smaller than our MCR estimate of 0.21 ± 0.04°C per effective Pg CH$_4$ removed (figure 2). Accounting for the time delay for carbon dioxide removal due to the lagged response of the deep ocean, the TCRE for CO2 removal may be even lower [39]. If 1 year of anthropogenic emissions was removed (0.36 Pg CH$_4$ [3] and 41.4 Pg CO$_2$ [40]), the transient temperature impact would be almost four times larger for methane than for CO$_2$ (0.075°C compared to 0.02°C). Using this example, however, maintaining a steady-state response of 0.36 Pg CH$_4$ effectively removed would require the ongoing removal of roughly 0.03Pg CH$_4$ yr^{-1}, since a removal rate of E/τ is required to maintain an effective cumulative removal of E.").

[297] Saunois M., *et al.* (2020) *The Global Methane Budget* 2000-2017, Earth Syst. Sci. Data 12(3): 1561–1623, 1561 ("For the 2008–2017 decade, global methane emissions are estimated by atmospheric inversions (a top-down approach) to be 576 Tg CH$_4$ yr^{-1} (range 550–594, corresponding to the minimum and maximum estimates of the model ensemble). Of this total, 359 Tg CH$_4$ yr^{-1} or ~ 60 % is attributed to anthropogenic sources, that is emissions caused by direct human activity (i.e. anthropogenic emissions; range 336–376 Tg CH$_4$ yr^{-1} or 50 %–65 %).").

[298] Abernethy S., O'Connor F. M., Jones C. D., & Jackson R. B. (2021) *Methane removal and the proportional reductions in surface temperature and ozone*, Philos. Trans. R. Soc. A 379(2210): 1–13, 6 ("Due to the temporal nature of effective cumulative removal, comparisons between methane and carbon dioxide depend on the timescale

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[299] U.S. National Academies of Sciences, Engineering, and Medicine, *Atmospheric Methane Removal: Development of a Research Agenda* (*last visited* 28 August 2023).

[300] Secretariat of the United Nations Framework Convention on Climate Change, *External Press Release, World Leaders Kick Start Accelerated Climate Action at COP26* (2 November 2021) ("Today is also the first time a COP in recent history has hosted a major event on methane, with 103 countries, including 15 major emitters including Brazil, Nigeria and Canada, signing up to the Global Methane Pledge.").

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

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

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

[304] William + Flora Hewlett Foundation (11 October 2021, updated 2 November 2021) *Leading Philanthropic Organizations Partner and Commit to Over $328M to Reducing Methane Emissions*, Press Release.

[305] Global Methane Hub, *Pledge* (*last visited* 28 August 2023) ("**The Global Methane Pledge is an initiative launched in 2021, to reduce global methane emissions and keep the goal of limiting warming to 1.5 degrees Celsius within reach.** The United States, European Union and over 110 countries have signed the pledge, which represents more than 70% of the global economy and half of anthropogenic methane emissions. The Global Methane Hub, while independent from the pledge, will support those countries that want to make that pledge a reality, and those who want to go beyond.").

[306] United States Department of State (11 October 2021) *Joint U.S.-EU Statement on the Global Methane Pledge* ("Countries joining the Global Methane Pledge commit to a collective goal of reducing global methane emissions by

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at least 30 percent from 2020 levels by 2030 and moving towards using highest tier IPCC good practice inventory methodologies to quantify methane emissions, with a particular focus on high emission sources. Successful implementation of the Pledge would reduce warming by at least 0.2 degrees Celsius by 2050.”).

[307] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS, 9 (“Currently available measures could reduce emissions from these major sectors by approximately 180 Mt/yr, or as much as 45 per cent, by 2030. This is a cost-effective step required to achieve the United Nations Framework Convention on Climate Change (UNFCCC) 1.5° C target. According to scenarios analysed by the Intergovernmental Panel on Climate Change (IPCC), global methane emissions must be reduced by between 40–45 per cent by 2030 to achieve least cost-pathways that limit global warming to 1.5° C this century, alongside substantial simultaneous reductions of all climate forcers including carbon dioxide and short-lived climate pollutants. (Section 4.1).”).

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

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

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

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

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

[313] *See* Inflation Reduction Act, Pub. L. No. 117-169, §21001, 60114 (2022); United States Senate (28 July 2022) *Summary of the Energy Security and Climate Change Investments in the Inflation Reduction Act of 2022*; *and* United States White House (2023) *BUILDING A CLEAN ENERGY ECONOMY: A GUIDEBOOK TO THE INFLATION REDUCTION ACT'S INVESTMENTS IN CLEAN ENERGY AND CLIMATE ACTION*, Version 2, 68 ("$1.55 billion to cut methane pollution from oil and gas industry operations. EPA received $1.55 billion to provide financial and technical assistance to accelerate the reduction of methane and other greenhouse gas emissions from petroleum and natural gas systems by improving and deploying new equipment, supporting technological innovation, permanently shutting in and plugging wells, and other activities. In addition to these financial incentives, the Inflation Reduction Act imposes a waste emissions charge on facilities with methane emissions that exceed a certain threshold. This EPA program complements nearly $4.7 billion in the Bipartisan Infrastructure Law to plug and remediate orphaned oil and gas wells on Tribal, federal, state, and private lands."). For further information on what is in the 2022 Inflation Reduction Act, *see* Paris F., Parlapiano A., Sanger-Katz M., & Washington E. (13 August 2022, *updated* 16 August 2022) *A Detailed Picture of What's in the Democrats' Climate and Health Bill*, THE NEW YORK TIMES.

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

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

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

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

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

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

[320] Feng Z., Xu Y., Kobayashi K., Dai L., Zhang T., Agathokleous E., Calatayud V., Paoletti E., Mukherjee A., Agrawal M., Park R. J., Oak Y. J., & Yue X. (2022) *Ozone pollution threatens the production of major staple crops in East Asia*, NAT. FOOD 3: 47–56, 47 ("East Asia is a hotspot of surface ozone (O_3) pollution, which hinders crop growth and reduces yields. Here, we assess the relative yield loss in rice, wheat and maize due to O_3 by combining O_3 elevation experiments across Asia and air monitoring at about 3,000 locations in China, Japan and Korea. China shows the highest relative yield loss at 33%, 23% and 9% for wheat, rice and maize, respectively. The relative yield loss is much greater in hybrid than inbred rice, being close to that for wheat. Total O_3-induced annual loss of crop production is estimated at US$63 billion."). *See also* United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS, 68 ("Methane also plays a significant role in reducing crop yields and the quality of vegetation. Ozone exposure is estimated to result in yield losses in wheat, 7.1 per cent; soybean,12.4 per cent; maize, 6.1 per cent; and rice, 4.4 per cent for near present-day global totals (Mills et al. 2018; Shindell et al. 2016; Avnery et al. 2011a)"); *and* Shindell D., Faluvegi G., Kasibhatla P., & Van Dingenen R. (2019) *Spatial Patterns of Crop Yield Change by Emitted Pollutant*, EARTH'S FUTURE 7(2): 101–112, 101 ("Our statistical modeling indicates that for the global mean, climate and composition changes have decreased wheat and maize yields substantially whereas rice yields have increased. Well-mixed greenhouse gasses drive most of the impacts, though aerosol-induced cooling can be important, particularly for more polluted area including India and China. Maize yield losses are most strongly attributable to methane emissions (via both temperature and ozone).").

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[321] Mar K. A., Unger C., Walderdorff L., & Butler T. (2022) *Beyond CO_2 equivalence: The impacts of methane on climate, ecosystems, and health*, ENV. SCI. POL. 134: 127–136, 129 ("Methane is an important contributor to the formation of tropospheric O_3. In addition to acting as a greenhouse gas and being directly harmful to human health (see Section 3.3), it also harms plants by causing cellular damage within the leaves, adversely affecting plant production, reducing the rate of photosynthesis, and requiring increased resource allocation to detoxify and repair leaves (Ashmore, 2005, Sitch et al., 2007). This results in an estimated $11-$18 billion worth of global crop losses annually (Avnery et al., 2011). Beyond this, however, O_3 damage to plants may significantly reduce the ability of terrestrial ecosystems to absorb carbon, negating some of the enhanced carbon uptake due to CO_2 fertilization that is expected to partially offset rising atmospheric CO_2 concentrations (Sitch et al., 2007, Ciais et al., 2013, Arneth et al., 2010, Ainsworth et al., 2012)."). *See also* Szopa S., Naik V., Adhikary B., Artaxo P., Berntsen T., Collins W. D., Fuzzi S., Gallardo L., Kiendler-Scharr A., Klimont Z., Liao H., Unger N., & Zanis P. (2021) *Chapter 6: Short-lived climate forcers*, in CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 857 ("Ozone uptake itself damages photosynthesis and reduces plant growth with consequences for the carbon and water cycles (Ainsworth et al., 2012; Emberson et al., 2018).… Tropospheric aerosols influence the land and ocean ecosystem productivity and the carbon cycle through changing physical climate and meteorology (Jones, 2003; Cox et al., 2008; Mahowald, 2011; Unger et al., 2017) and through changing deposition of nutrients including nitrogen, sulphur, iron and phosphorous (Mahowald et al., 2017; Kanakidou et al., 2018). There is robust evidence and high agreement from field (Oliveira et al., 2007; Cirino et al., 2014; Rap et al., 2015; X. Wang et al., 2018) and modelling (Mercado et al., 2009; Strada and Unger, 2016; Lu et al., 2017; Yue et al., 2017) studies that aerosols affect plant productivity through increasing the diffuse fraction of downward shortwave radiation, although the magnitude and importance to the global land carbon sink is controversial. At large scales the dominant effect of aerosols on the carbon cycle is likely a global cooling effect of the climate (medium confidence) (Jones, 2003; Mahowald, 2011; Unger et al., 2017). We assess that these interactions between aerosols and the carbon cycle are currently too uncertain to constrain quantitatively the indirect CO2 forcing. In summary, reactive nitrogen, ozone and aerosols affect terrestrial vegetation and the carbon cycle through deposition and effects on large-scale radiation (high confidence) but the magnitude of these effects on the land carbon sink, ecosystem productivity and indirect CO2 forcing remain uncertain due to the difficulty in disentangling the complex interactions between the effects. As such, we assess the effects to be of second order in comparison to the direct CO2 forcing (high confidence) but, at least for ozone, it could add a substantial (positive) forcing compared with its direct forcing (low confidence).").

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

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

[324] Mar K. A., Unger C., Walderdorff L. & Butler T. (2022) *Beyond CO_2 equivalence: The impacts of methane on climate, ecosystems, and health*, ENVT'L. SCIENCE & POL'Y 134: 127–136, 130 ("Importantly, the role of methane's contribution to O_3 production is expected to increase in the future, as emissions of other anthropogenic precursors (primarily NO_x and VOCs) are anticipated to decrease as a result of current and planned air quality regulations across

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much of the globe. For instance, Young et al. (2013) showed that rising CH_4 concentrations could be a major driver of increased surface O_3 by 2100 under the high-emission scenario developed for the IPCC 5th Assessment report. Turnock et al. (2018) showed that increased O_3 production from rising CH_4 concentrations could offset the reduction in surface O_3 due to reductions in emissions of shorter-lived O_3 precursors.”).

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

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

[327] Bond T. C., *et al.* (2013) *Bounding the role of black carbon in the climate system: A scientific assessment*, J. GEOPHYS. RES. ATMOS. 118(11): 5380–5552, 5420 (“Major sources of BC are also major sources of $PM_{2.5}$, but the converse is not always true; major sources of $PM_{2.5}$ may produce little BC if their emissions are primarily inorganic. Sources that are BC and OC emitters are shown in the table. Resuspended dust, secondary pollutants like sulfate and nitrate, or sea salt, could also be contributors to PM2.5 at some locations but are not included in Table 11.”); major sources in Table 11 include (in order of decreasing importance): transport (vehicle exhaust including gasoline and diesel); IN = industry including coal and oil and biomass burning; coal burning power plants; RE = residential energy; OB= open burning of biomass and refuse; SA = secondary aerosols; O= Others.

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

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

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

[331] 1999 Protocol to Abate Acidification, Eutrophication and Ground-Level Ozone (Gothenburg Protocol), Decision 2012/8: Adoption of guidance document on control techniques for emissions of sulphur, nitrogen oxides, volatile organic compounds and particulate matter (including PM_{10}, $PM_{2.5}$, and black carbon) from stationary sources. *See also* Matthews B. & Paunu V.-V. (2019) *Review of Reporting Systems for National Black Carbon Emissions Inventories*, EU Action on Black Carbon in the Arctic - Technical Report 2, 1–2 (“Emissions reporting systems are thus in need of further improvement. In evaluating needs for improvement, the EU Action on Black Carbon in the Arctic review identified the following priority areas . . . 4. Enhanced cooperation between CLRTAP and the Arctic Council to expand

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and harmonise black carbon emissions reporting by countries whose black carbon emissions impact the Arctic."). *Compare with* Expert Group on Black Carbon and Methane (2019) *Summary of Progress and Recommendations*, Arctic Council Secretariat, 32 (Table 5, *showing* U.S. with 9.5bcm of flaring based on World Bank satellite observations); *and* Energy Information Administration, *Natural Gas Gross Withdrawals and Production* (*last visited* 10 June 2023) (showing combined flaring and venting volumes of 255bcm for 2017).

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

[333] Clean Air Task Force, *Oil and Gas Mitigation Program* (*last visited* 13 June 2023) ("Operators often vent and flare natural gas at oil wells. This waste occurs when oil producers, driven by the rush to Operators often vent and flare natural gas at oil wells. This waste occurs when oil producers, driven by the rush to sell oil, simply dispose of the gas from producing oil wells instead of building infrastructure (such as pipelines) to capture gas as soon as production begins. (In some cases, pipelines are never built and all of the gas the well produces over its lifetime is wasted in this way, as can be seen in sales records for individual wells available from state regulators.) While a substantial portion of this gas is flared off — wasting energy and producing large amounts of carbon dioxide and other pollutants — some is just dumped into the air, or vented. Even in cases where a gas pipeline is not connected, there are a variety of other technologies that operators can use to reduce associated gas flaring at oil wells. Venting is even more harmful than flaring, since methane warms the climate so powerfully, and VOC and toxic pollutants are released unabated. Venting of this gas should be prohibited in all cases as an absolutely unnecessary source of harmful air pollution. There are numerous lowcost (and usually profitable) ways to utilize natural gas from oil wells. Flaring should be a last resort: only in the most extreme cases should oil producers be allowed to flare gas, and it should be strictly a temporary measure. Rules prohibiting venting of natural gas can easily reduce emissions by 95%."). *See also* World Bank, *Zero Routine Flaring by 2030 Initiative Text* (*last visited* 13 June 2023) ("This "**Zero Routine Flaring by 2030" initiative** (the Initiative), introduced by the World Bank, brings together governments, oil companies, and development institutions who recognize the flaring situation described above is unsustainable from a resource management and environmental perspective, and who agree to cooperate to eliminate routine flaring no later than 2030."); *and* Saunier S., Bergauer M-A., & Isakova I. (2019) *Best Available Techniques Economically Achievable to Address Black Carbon from Gas Flaring*, EU Action on Black Carbon in the Arctic Technical Report 3, 3 ("Although the effectiveness of BATEA largely depends on site-specific economic and technical parameters, they have a substantial potential to achieve meaningful and measurable environmental and financial benefits. Quantifying resultant reductions in BC emissions as a result of mitigation strategies remains challenging, however, implementing BATEA should still be considered a best practice for reducing flaring-associated BC emissions. Along with other newly available technologies, use of the BATEA described herein will support existing efforts to mitigate short-term climate change, as well as address other energy, environmental, and safety issues that are likely to result from gas flaring in Arctic regions.").

[334] International Energy Agency, International Renewable Energy Agency, United Nations Statistics Division, World Bank, & World Health Organization (2020) TRACKING SDG 7: THE ENERGY PROGRESS REPORT, 6 ("The share of the

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

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

[336] Velders G. J. M., Andersen S. O., Daniel J. S., Fahey D. W., & McFarland M. (2007) *The importance of the Montreal Protocol in protecting climate*, Proc. Nat'l. Acad. Sci. 104(12): 4814–4819, 4816 ("In contrast, without the early warning of the effects of CFCs (MR74 scenario), estimated ODS emissions would have reached 24–76 GtCO$_2$-eq yr 1 in 2010. Thus, in the current decade, in a world without ODS restrictions, annual ODS emissions using only the GWP metric could be as important for climate forcing as those of CO$_2$."). *See also* Sigmond M., Polvani L. M., Fyfe J. C., Smith C. J., Cole J. N. S., & England M. R. (2023) *Large Contribution of Ozone-Depleting Substances to Global and Arctic Warming in the Late 20th Century*, Geophys. Res. Lett. 50(5): 1–9, 4, 5 ("Furthermore, we place the warming from ODSs in the broader context of the total anthropogenic warming (which includes well mixed GHGs and ozone, and excludes the cooling effects of aerosols, see the previous section). The warming from all anthropogenic forcings (labeled "AntW" in Figure 2) is found to be 1.26°C in the ensemble mean. ODSs, therefore, have contributed nearly one third (30%) of the total anthropogenic warming over the 1955 to 2005 period. … This second key result of our study, the high efficacy of ODSs, stands in contrast to the result obtained from highly idealized equilibrium forcing experiments (Richardson et al., 2019), which have reported an efficacy for CFC11 and CFC12 close to unity. Analyzing the realistic transient evolution of historical forcings over the 1955–2005 period, our model shows that ODSs are almost 20% more effective at warming global temperatures than carbon dioxide.").

[337] England M. R. & Polvani L. M. (2023) *The Montreal Protocol is delaying the occurrence of the first ice-free Arctic summer*, Proc. Nat'l. Acad. Sci. 120(22): e2211432120, 1 ("Current projections indicate that the first ice-free Arctic summer will likely occur by mid-century, owing to increasing carbon dioxide concentrations in the atmosphere.

However, other powerful greenhouse gases have also contributed to Arctic sea ice loss, notably ozone-depleting substances (ODSs). In the late 1980s ODSs became strictly regulated by the Montreal Protocol, and their atmospheric concentrations have been declining since the mid-1990s. Here, analyzing new climate model simulations, we demonstrate that the Montreal Protocol, designed to protect the ozone layer, is delaying the first appearance of an ice-free Arctic summer, by up to 15 years, depending on future emissions. We also show that this important climate mitigation stems entirely from the reduced greenhouse gas warming from the regulated ODSs, with the avoided stratospheric ozone losses playing no role. Finally, we estimate that each Gg of averted ODS emissions results in approximately 7 km^2 of avoided Arctic sea ice loss.").

[338] Young P. J., Harper A. B., Huntingford C., Paul N. D., Morgenstern O., Newman P. A., Oman L. D., Madronich S., & Garcia R. R. (2021) *The Montreal Protocol protects the terrestrial carbon sink*, NATURE 596(7872): 384–388, 384 ("Overall, at the end of the century, worldAvd warms by an additional 2.5 K (2.4–2.7 K) above the RCP 6.0 baseline in worldProj. Of this warming, 1.7 K comes from the previously explored19 additional radiative forcing due to the higher CFC concentrations in worldProj. Newly quantified here is the additional warming of global-mean air temperature of 0.85 K (0.65–1.0 K)—half as much again—that arises from the higher atmospheric CO_2 concentrations due to the damaging effect of UV radiation on terrestrial carbon stores."). *See also* United Nations Environment Programme, Ozone Secretariat (16 September 2022) *World Ozone Day 2022: Global cooperation protecting life on Earth* ("This action has protected millions of people from skin cancer and cataracts over the years since. It allowed vital ecosystems to survive and thrive. It safeguarded life on Earth. And it slowed climate change: if ozone-depleting chemicals had not been banned, we would be looking at a global temperature rise of an additional 2.5°C by the end of this century. This would have been a catastrophe."); World Meteorological Organization, United Nations Environment Programme, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, & European Commission (2022) SCIENTIFIC ASSESSMENT OF OZONE DEPLETION: 2022, Global Ozone Research and Monitoring Project–Report No. 278, WMO, 26 ("New studies support previous Assessments in that the decline in ODS emissions due to compliance with the Montreal Protocol avoids global warming of approximately 0.5–1 °C by mid-century compared to an extreme scenario with an uncontrolled increase in ODSs of 3–3.5% per year."); *and* Andersen S. O., Gonzalez M., & Sherman N. J. (18 October 2022) *Setting the stage for climate action under the Montreal Protocol*, EOS 103.

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

[340] England M. R. & Polvani L. M. (2023) *The Montreal Protocol is delaying the occurrence of the first ice-free Arctic summer*, PROC. NAT'L. ACAD. SCI. 120(22): e2211432120, 1 ("Current projections indicate that the first ice-free Arctic summer will likely occur by mid-century, owing to increasing carbon dioxide concentrations in the atmosphere. However, other powerful greenhouse gases have also contributed to Arctic sea ice loss, notably ozone-depleting substances (ODSs). In the late 1980s ODSs became strictly regulated by the Montreal Protocol, and their atmospheric concentrations have been declining since the mid-1990s. Here, analyzing new climate model simulations, we demonstrate that the Montreal Protocol, designed to protect the ozone layer, is delaying the first appearance of an ice-free Arctic summer, by up to 15 years, depending on future emissions. We also show that this important climate mitigation stems entirely from the reduced greenhouse gas warming from the regulated ODSs, with the avoided stratospheric ozone losses playing no role. Finally, we estimate that each Gg of averted ODS emissions results in approximately 7 km^2 of avoided Arctic sea ice loss."), *See also* Sigmond M., Polvani L. M., Fyfe J. C., Smith C. J., Cole J. N. S., & England M. R. (2023) *Large Contribution of Ozone-Depleting Substances to Global and Arctic Warming in the Late 20th Century*, GEOPHYS. RES. LETT. 50(5): 1–9, 4, 5 ("Furthermore, we place the warming from ODSs in the broader context of the total anthropogenic warming (which includes well mixed GHGs and ozone, and excludes the cooling effects of aerosols, see the previous section). The warming from all anthropogenic forcings (labeled "AntW" in Figure 2) is found to be 1.26°C in the ensemble mean. ODSs, therefore, have contributed nearly one third (30%) of the total anthropogenic warming over the 1955 to 2005 period. … This second key result of our

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

[341] Sigmond M., Polvani L. M., Fyfe J. C., Smith C. J., Cole J. N. S., & England M. R. (2023) *Large Contribution of Ozone-Depleting Substances to Global and Arctic Warming in the Late 20th Century*, Geophys. Res. Lett. 50(5): 1–9, 5 ("Fixing ODSs to 1955 levels reduces 1955–2005 Arctic warming by 55% (45%–68%) and September sea ice extent decline by 45% (18%–67%), in good agreement with the values reported in Polvani et al. (2020). ODSs are found to be responsible for 1.15°C of the Arctic mean warming, which amounts to 66% of Arctic warming due to CO_2, and to 37% of the Arctic warming that is due to all anthropogenic warming agents. The ratio of Arctic relative to the global mean warming, referred to as Arctic amplification factor, is 2.99 (2.49–3.53) for ODSs, which is slightly larger than for CO_2 (2.78, 2.45–3.12), consistent with a previous study (Liang et al., 2022). However the difference is not statistically significant in our model. As for September sea ice extent, we find that ODSs are responsible for 0.82 million km2of its decline, which is 33% of the decline due to all anthropogenic warming. In summary, more than a third of changes in key Arctic climate indicators between 1955 and 2005 can be attributed to ODS increases."). *See also* Polvani L. M., Previdi M., England M. R., Chiodo G., & Smith K. L. (2020) *Substantial twentieth-century Arctic warming caused by ozone-depleting substances*, Nat. Clim. Chang. 10(2): 130–133, 133 ("Without the large cancellation from aerosols the relative contribution of ODS to the total forced Arctic climate change would be smaller. However, irrespective of aerosols, the absolute contribution of ODS—nearly 0.8 °C of warming and 0.7×106 km2 of September sea ice loss over only 50 years—is remarkably large. In conclusion, if our findings are confirmed by future studies, the role of the Montreal Protocol as a major environmental treaty will assume a new dimension. Our model integrations show that, in addition to being the key drivers of stratospheric ozone depletion (notably over the South Pole), ODS have been important players in the global climate system, notably in the Arctic, over the second half of the twentieth century. Our findings also have implications for the future because the phase-out of ODS, which is well under way, will substantially mitigate Arctic warming and sea-ice melting in the coming decades.").

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

[343] Western L. M., *et al.* (2023) *Global increase of ozone-depleting chlorofluorocarbons from 2010 to 2020*, Nat. Geosci. 16: 309–313, 312 ("Combined global emissions of CFC-13, CFC-112a, CFC-113a, CFC-114a and CFC-115 increased from 1.6 ± 0.2 to 4.2 ± 0.4 ODP-Gg yr^{-1} (ODP-Gg, mass weighted by their CFC-11-equivalent ozone-depleting potential (ODP)) between 2010 and 2020 (Fig. 2). The mean growth rate of these emissions is around 0.3 ODP-Gg yr^{-1} per year. Global emissions of CFC-11 increased between the periods 2008–2012 and 2014–2018[5,19] which were attributed to unreported production. The increase in global emissions between 2010 and 2020 of the five CFCs reported here (expressed as ODP-Gg yr^{-1}) is around a fifth of the global increase in CFC-11. In terms of impact on climate, the five CFC emissions derived for 2020 are equivalent to 47 ± 5 $TgCO_2$-equivalent (CO_2e) yr^{-1} in 2020 (around 150% of London's CO_2 emissions in 2018[20] based on 100 yr global warming potentials). … Ozone-depleting substances used as feedstocks and produced as by-products are not subject to the same controls on production as those for so-called dispersive use under the Montreal Protocol. As such, there is no current barrier to future use in the

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synthesis of chemicals. In the absence of further evidence, it is likely that the rapidly rising emissions of the long-lived ozone-depleting CFCs identified here are from processes not subject to current controls under the Montreal Protocol.”).

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

[345] Montzka S. A., Velders G. J. M., Krummel P. B., Mühle J., Orkin,V. L., Park S., Shah N., & Walter-Terrinoni H. (2018) *Chapter 2: Hydrofluorocarbons (HFCs), in* Scientific Assessment of Ozone Depletion: 2018, Global Ozone Research and Monitoring Project–Report No. 58, World Meteorological Organization, United Nations Environment Programme, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, & European Commission, 2.40–2.41 (“With the Kigali Amendment and national and regional regulations, the future production and consumption of HFCs is strongly limited (Table 2-1). Under the provisions of the Amendment, the contribution of HFCs to the global average surface temperature is projected to reach a maximum around 2060, after which it slowly decreases to about 0.06°C by 2100 (Figure 2-20). In contrast, the surface temperature contribution from HFCs in the baseline scenario is 0.3–0.5°C in 2100 (based on Xu *et al.*, 2013 and Velders *et al.*, 2015). The difference in projected temperatures is relevant in the context of the 2015 UNFCCC Paris Agreement, which aims to limit the global temperature increase to well below 2°C relative to pre-industrial levels.”). *See also* World Meteorological Organization, United Nations Environment Programme, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, & European Commission (2022) Scientific Assessment of Ozone Depletion: 2022, Global Ozone Research and Monitoring Project–Report No. 278, WMO, 21 (“Following the controls of the Kigali Amendment, HFC emissions (excluding HFC-23) in 2050 are projected to be 0.9–1.0 Gt CO_2-eq. yr^{-1} in the updated 2022 Kigali Amendment scenario, compared to 4.0–5.3 Gt CO_2eq yr^{-1} in the 2018 scenario without control measures (Figure ES-4). The corresponding radiative forcing in 2050 due to HFCs is 0.09–0.10 W m^{-2} with adherence to the Kigali Amendment, compared to 0.22–0.25 W m^{-2} without control measures. Annual average surface warming from HFCs is expected to be 0.04 °C in 2100 under the updated 2022 Kigali Amendment scenario, compared to 0.3–0.5 °C without control measures.”); *and* Liang Q., Rigby M., Fang X., Godwin D., Mühle J., Saito T., Stanley K. M., Velders G. J. M., Bernath P., Derek N., Reimann S., Simpson I. J., & Western L. (2022) *Chapter 2: Hydrofluorocarbons (HFCs), in* Scientific Assessment of Ozone Depletion: 2022, Global Ozone Research and Monitoring Project–Report No. 278, World Meteorological Organization, United Nations Environment Programme, National Oceanic and Atmospheric Administration, National Aeronautics and

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Space Administration, & European Commission, 143 ("In the new scenario following current trends, national policies, and the provisions of the Kigali Amendment, the HFCs are projected to contribute 0.04°C to the global average surface warming in 2100, compared to 0.3– 0.5°C in the baseline scenarios of the previous Assessment (Montzka, Velders et al., 2018; Velders et al., 2022). The updated Kigali Amendment scenario leads to a temperature rise that is slightly lower than that of the previous Assessment. For comparison, all greenhouse gases (GHGs) are projected to contribute 1.4–4.4°C to surface warming by the end of the 21st century, following the IPCC scenarios (best estimate for 2081–2100; IPCC, 2021). In hypothetical scenarios with a cease in global production or emissions of HFCs in 2023, the contribution to surface warming is reduced to no more than 0.01°C in 2100.").

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

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

[348] World Meteorological Organization, United Nations Environment Programme, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, & European Commission (2018) SCIENTIFIC ASSESSMENT OF OZONE DEPLETION: 2018, Global Ozone Research and Monitoring Project Report No. 58, World Meteorological Organization, ES-22, 2.40–2.41 ("The Kigali Amendment is projected to reduce future global average warming in 2100 due to HFCs from a baseline of 0.3-0.5 ºC to less than 0.1 ºC (Figure ES-4). If the global production of HFCs were to cease in 2020, the surface temperature contribution of the HFC emissions would stay below 0.02 ºC for the whole 21st century. The magnitude of the avoided temperature increase, due to the provisions of the Kigali Amendment (0.2 to 0.4 ºC) is substantial in the context of the 2015 UNFCCC Paris Agreement, which aims to limit global temperature rise to well below 2.0 ºC above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 ºC. … With the Kigali Amendment and national and regional regulations, the future production and consumption of HFCs is strongly limited (Table 2-1). Under the provisions of the Amendment, the

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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.").

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

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

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

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

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

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[354] *See* HFCBans.com (*last visited* 14 June 2023) (States with finalized HFC prohibitions include: California, Colorado, Delaware, Maine, Maryland, Massachusetts, New Jersey, New York, Rhode Island, Washington, Vermont, and Virginia. States with proposed bans include: Connecticut, Hawaii, New Mexico, Oregon, Pennsylvania, and Texas.).

[355] 168 CONG. REC. D1,006 (daily ed. Sept. 21, 2022) ("By 69 yeas to 27 nays (Vote No. EX. 343), two-thirds of the Senators present having voted in the affirmative, Senate agreed to the resolution of Advise and Consent to Ratification, as amended, to Treaty Document 117–1, the amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer (the ''Montreal Protocol''), adopted at Kigali on October 15, 2016, by the Twenty-Eighth Meeting of the Parties to the Montreal Protocol (the ''Kigali Amendment''), with 1 declaration…"). *See also* White House (21 September 2022) *Statement by President Joe Biden on Senate Ratification of the Kigali Amendment to the Montreal Protocol*; *and* White House (16 November 2021) *A Message to the Senate on the Amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer*, Briefing Room ("TO THE SENATE OF THE UNITED STATES: With a view to receiving the advice and consent of the Senate to ratification, I transmit herewith the Amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer (the "Montreal Protocol"), adopted at Kigali on October 15, 2016, by the Twenty-Eighth Meeting of the Parties to the Montreal Protocol (the "Kigali Amendment"). The report of the Department of State is also enclosed for the information of the Senate. The principal features of the Kigali Amendment provide for a gradual phasedown in the production and consumption of hydrofluorocarbons (HFCs), which are alternatives to ozone-depleting substances being phased out under the Montreal Protocol, as well as related provisions concerning reporting, licensing, control of trade with non-Parties, and control of certain byproduct emissions."), *discussed in* Mason J. (16 November 2021) *White House sends Kigali amendment on climate-warming gases to Senate*, REUTERS.

[356] Forster P., *et. al.* (2021) *Chapter 7: The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS (*see* Table 7.15 on the emission metrics for a select species of gases, including methane and nitrous oxide (N_2O).).

[357] Compare the global mean effective radiative forcing values under AR6 for CO_2 and N_2O: Forster P., *et. al.* (2021) *Chapter 7: The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, Table 7.8.

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

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

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

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[361] Harmsen J. H. M., van Vuuren D. P., Nayak D. R., Hof A. F., Höglund-Isaksson L., Lucas P. L., Nielsen J. B., Smith P., & Stehfest E. (2019) *Long-term marginal abatement cost curves of non-CO_2 greenhouse gases*, ENVIRON. SCI. POLICY 99: 136–149, 145 (Table 2).

[362] World Meteorological Organization, United Nations Environment Programme, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, & European Commission (2022). SCIENTIFIC ASSESSMENT OF OZONE DEPLETION: 2022, Global Ozone Research and Monitoring Project– GAW Report No. 278, World Meteorological Organization, 393 ("A reduction in future N_2O emissions from that in the baseline scenario (SSP2-4.5) to that in the SSP scenario with the strongest N_2O mitigation (SSP1-1.9) results in a 0.5 DU increase in ozone averaged over 2020 to 2070, or about one-quarter of the impact of eliminating all emissions from controlled ODSs beginning in 2023. This emission reduction also leads to a radiative forcing reduction of 43 mW m^{-2} averaged over 2023–2100. The magnitude of this N_2O reduction represents a decrease in anthropogenic N_2O emissions of 3% compared with the baseline scenario when averaged over 2020 –2070.").

[363] World Meteorological Organization, United Nations Environment Programme, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, & European Commission (2022). SCIENTIFIC ASSESSMENT OF OZONE DEPLETION: 2022, Global Ozone Research and Monitoring Project– GAW Report No. 278, World Meteorological Organization, 394 (*see* Figure 7-1 showing that N_2O emissions reduction to SSP1-1.9 results in a decrease in radiative forcing of about 0.04 W m^{-2} while eliminating all high-GWP HFC emissions results in a decrease in radiative forcing of about 0.07 Wm^{-2}).

[364] World Meteorological Organization, United Nations Environment Programme, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, & European Commission (2022). SCIENTIFIC ASSESSMENT OF OZONE DEPLETION: 2022, Global Ozone Research and Monitoring Project– GAW Report No. 278, World Meteorological Organization, 258 ("Therefore, in general, the ozone return date is expected to be later if there are increases in N_2O or earlier if there are decreases in N_2O. However, the effect of future increases in N_2O varies with altitude and also depends on the temporal evolution of other GHGs."). *See also* Butler A. H., Daniel J. S., Portmann R. W., Ravishankara A. R., Young P. J., Fahey D. W., & Rosenlof K. H. (2016) *Diverse policy implications for future ozone and surface UV in a changing climate*, ENV. RES. LETT. 11(6): 064017, 1–7, 4 ("A key point is that if the world were to achieve reductions of CO_2 and CH_4 concentrations to RCP 2.6 levels, N_2O mitigation would become important to avoid exacerbation of both climate change and ozone layer depletion.").

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

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

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

[368] Dreyfus G., Frederick C., Larkin E., Powers Y., & Chatterjee J. (2023) *Reducing nitrous oxide emissions from smallholder farmer agriculture through site specific nutrient management,* Precision Development & Institute for Governance & Sustainable Development, 3 ("Addressing the precision nutrient management gap for smallholder farmers in the Global South is a critical priority for achieving both anti-poverty and climate change goals, especially as the use of nitrogen fertilizer in Global South countries rises[15] in coming years to meet increasing global food demands.").

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

[370] *See* Peterson C., El Mashad H. M., Zhao Y., Pan Y., & Mitloehner F. M. (2020) *Effects of SOP Lagoon Additive on Gaseous Emissions from Stored Liquid Dairy Manure*, Sustainability 12(4): 1–17, 14–15 ("These studies seem to indicate that the applied HIGH dose of SOP Lagoon might decrease the number of methanogens that produce methane during the storage of manure as well as hydrolytic microorganisms and their excreted enzymes that biodegrade organic nitrogen into ammonium."); *and* Maris S. C., Capra F., Ardenti F., Chiodini M. E., Boselli R., Taskin E., Puglisi E., Bertora C., Poggianella L., Amaducci S., Tabaglio V., & Fiorini A. (2021) *Reducing N Fertilization without Yield Penalties in Maize with a Commercially Available Seed Dressing*, Agronomy 11(3): 407, 1–19, 1 ("[W]e concluded that under our experimental conditions SCM [SOP® COCUS MAIZE+] may be used for reducing N [nitrogen] input (-30%) and N$_2$O emissions (-23%), while contemporarily maintaining maize yield. Hence, SCM can be considered an available tool to improve agriculture's alignment to the United Nation Sustainable Development Goals (UN SDGs) and to comply with Europe's Farm to Fork strategy for reducing N-fertilizer inputs."). *See also* SOP, Save Our Planet, *Read the SOP Scientific Works* (*last visited* 28 August 2023).

[371] United States Environmental Protection Agency (2019) Global Non-CO$_2$ Greenhouse Gas Emission Projections & Mitigation: 2015–2050, 28 ("The global abatement potential is 231 MtCO$_2$e, or 86% of projected emissions in 2030.").

[372] Environmental Protection Agency (2012) Global Anthropogenic Non-CO$_2$ Greenhouse Gas Emissions: 1990–2030, 41 ("Between 1990 and 2005, N$_2$O emissions from production of nitric and adipic acid has decreased 37 percent, from 200 MtCO$_2$e to 126 MtCO$_2$e (see Table 4-2). Over this time period, production of nitric and adipic acid has increased. The decline in historical emissions is mostly due to widespread installation of abatement technologies in the adipic acid industry (Reimer et al, 1999). Most production capacity in these industries has been located in the OECD, but the proportion of emissions in the OECD has declined. In 1990, the OECD accounted for 83 percent of global N$_2$Oemissions from this source, whereas the OECD is estimated to account for 68 percent of global emissions in 2005.").

[373] Environmental Protection Agency (2019) Global Non-CO$_2$ Greenhouse Gas Emission Projections & Mitigation: 2015–2050, 29 ("Taken together, the top 5 countries in terms of baseline emissions represent 85% of all potential global abatement in the source category in 2030. China alone represents 67% of total abatement potential, in part because of its high production capacity and lower adoption of emission controls relative to other large producers of nitric and adipic acid.").

[374] Hasanbeigi A. & Sibal A. (2023) Stopping a Super-Pollutant: N$_2$O Emissions Abatement from Global Adipic Acid Production, Global Efficiency Intelligence, 2, 9 ("There are estimated to be 39 operational facilities globally producing adipic acid while almost two thirds of the global adipic acid production takes place in China and U.S. Adipic acid production is one of the largest sources of nitrous oxide (N$_2$O) emissions. … Global facilities are currently abating N$_2$O emissions at different rates. Our key assumptions for the current abatement rates are as follow: ● U.S. adipic acid production: There are two adipic acid producers in the U.S. One reported to abate N$_2$O emissions at 97-99% rate in the last 5 years. We assumed a 98% abatement rate for this facility. The other plant's baseline abatement rate was assumed at 80%, which reflects a 5-year average (ClimeCo Corporation, 2019). ● Chinese adipic acid production: There are 11 producers of adipic acid in China. Several reports, in addition to expert testimony, led to the conclusion that Chinese adipic acid producers are not utilizing N$_2$O abatement technology (U.S. EPA, 2019, McKenna et al., 2020, Qing et al., 2020). ● Other countries' adipic acid production: For all others producers including Brazil, Japan, South Korea, France, Germany, and Italy we assumed abatement of 98% of N$_2$O emissions."); *as reported in* McKenna, P. (1 May 2023) *Eleven Chemical Plants in China and One in the U.S. Emit a Climate Super-Pollutant Called Nitrous Oxide That's 273 Times More Potent Than Carbon Dioxide*, Inside Climate News ("Neither the U.S. nor China require adipic acid manufacturers to reduce their nitrous oxide emissions."). *See also* McKenna, P., Pike, L., Northrop, K. (6 August 2020) *'Super-pollutant' emitted by 11 Chinese chemical plants could equal a climate catastrophe*, Inside Climate News ("Eleven adipic acid plants in China produce nearly half of the world's adipic acid… an Inside Climate News investigation, based on dozens of interviews and a review of hundreds

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of pages of documents from the Chinese government, the United Nations, and Chinese state media, strongly suggests that when funding for the U.N. program ended, so too did nearly all of the emissions reductions. This likely occurred despite the availability of proven, low-cost abatement technology. If the vast majority of the plants' emissions are released, unabated into the atmosphere, their collective emissions would exceed the yearly greenhouse gas emissions from all passenger vehicles in California, the most populous state in America, as well as the emissions from all cars in Beijing and Shanghai, China's two largest megacities.").

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

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

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

[378] Qian Y., Yasunari T. J., Doherty S. J., Flanner M. G., Lau W. K. M., Ming J., Wang H., Wang M., Warren S. G., & Zhang R. (2014) *Light-absorbing Particles in Snow and Ice: Measurement and Modeling of Climatic and Hydrological impact*, Adv. Atmos. Sci. 32: 64–91, 64 ("Light absorbing particles (LAP, e.g., black carbon, brown carbon, and dust) influence water and energy budgets of the atmosphere and snowpack in multiple ways. In addition to their effects associated with atmospheric heating by absorption of solar radiation and interactions with clouds, LAP in snow on land and ice can reduce the surface reflectance (a.k.a., surface darkening), which is likely to accelerate the snow aging process and further reduces snow albedo and increases the speed of snowpack melt. LAP in snow and ice (LAPSI) has been identified as one of major forcings affecting climate change, e.g. in the fourth and fifth assessment reports of IPCC. However, the uncertainty level in quantifying this effect remains very high. In this review paper, we document various technical methods of measuring LAPSI and review the progress made in measuring the LAPSI in Arctic, Tibetan Plateau and other mid-latitude regions. We also report the progress in modeling the mass concentrations, albedo reduction, radiative forcing, and climatic and hydrological impact of LAPSI at global and regional scales. Finally we identify some research needs for reducing the uncertainties in the impact of LAPSI on global and regional climate and the hydrological cycle."). *See also* Arctic Monitoring and Assessment Programme (2017) Adaptation Actions for a Changing Arctic: Perspectives from the Barents Area, 72 ("Highly reflective surfaces, such as snow and ice in the Arctic increase light absorption by BC particles in the atmosphere. BC also absorbs light after deposition onto (and then into) snow and ice, where it accelerates the melt process (Pedersen

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et al., 2015). BC has made an important contribution to the observed rise in Arctic surface temperature through the 20th century (although carbon dioxide is still the major factor driving the rise in Arctic temperature) (Quinn et al., 2008; Koch et al., 2011; AMAP, 2015a). It may be technically possible to reduce global anthropogenic BC emissions by up to 75% by 2030 (Shindell et al., 2012; AMAP, 2015a; Stohl et al., 2015). As well as helping to slow warming, BC emission reductions would also have significant health benefits (Anenberg et al., 2012; Shindell et al., 2012)."); International Energy Agency (2016) World Energy Outlook Special Report: Energy and Air Pollution, 115 ("Two areas of clear cross-benefit (for air quality and climate change) are actions to reduce emissions of black carbon, a major component of PM, and of methane (Box 3.4). Black carbon – emitted due to incomplete combustion, particularly from household biomass stoves and diesel vehicles – affects the climate in multiple ways. It absorbs incoming sunlight, leading to warming in the atmosphere, settles on the ground accelerating the melting of Arctic and alpine ice and, along with other pollutants that form aerosols, it affects the formation of clouds, so having a knock-on influence on increased warming."); *and* World Bank & International Cryosphere Climate Initiative (2013) On Thin Ice: How Cutting Pollution Can Slow Warming and Save Lives, 2 ("Climate benefits for cryosphere regions from black carbon reductions carry less uncertainty than they would in other parts of the globe and are sometimes very large. This is because emissions from sources that emit black carbon—even with other pollutants—almost always lead to warming over reflective ice and snow.").

[379] While this section focuses on warming from black carbon emitted by increased shipping in the Arctic, we note that use of high-sulfur heavy fuel oil in shipping has historically also contributed to sulfate aerosols and the formation of reflective ship tracks. The IMO has adopted regulations limiting sulfur content of shipping fuels, resulting in reduced cooling from sulfates and ship tracks. *See* Hansen J. E., Sato M., Simons L., Nazarenko L. S., Sangha I., von Schuckmann K., Loeb N. G., Osman M. B., Jin Q., Kharecha P., Tselioudis G., Jeong E., Lacis A., Ruedy R., Russell G., Cao J., & Li J. (23 May 2023) *Global warming in the pipeline*, IZV. Atmos. Ocean. Phys. (*preprint*): 1–62, 33 ("Changes of IMO emission regulations provide a great opportunity for insight into aerosol climate forcing. Sulfur content of fuels was limited to 1% in 2010 near the coasts of North America and in the North Sea, Baltic Sea and English Channel, and further restricted there to 0.1% in 2015. In 2020 a limit of 0.5% was imposed worldwide. The 1% limit did not have a noticeable effect on ship-tracks, but a striking reduction of ship-tracks was found after the 2015 IMO regulations, especially in the regions near land where emissions were specifically limited. Following the additional 2020 regulations, global ship-tracks were reduced more than 50%.").

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

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

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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.”).

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

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

[384] Arctic Council (2019) Expert Group on Black Carbon and Methane Summary Of Progress And Recommendations 2019, 13 (“At their 2017 meeting the Ministers of the Arctic Council member states adopted an expert group report that recommended a collective, aspirational goal to further reduce black carbon emissions by 25-33 percent relative to 2013 levels by 2025. “).

[385] Organisation for Economic Co-operation and Development (April 2021) The Economic Benefits of Air Quality Improvements in Arctic Council Countries, 13 (“Additional policies to extensively adopt the best available techniques would allow Arctic Council countries to reduce their emissions more substantially an dhalve their black carbon emissions by 2025, exceeding their collective target.

[386] Organisation for Economic Co-operation and Development (April 2021) The Economic Benefits of Air Quality Improvements in Arctic Council Countries, 46 (“According to the projections for 2050, with existing policies (the CKLE scenario), 8% of the population living in Arctic Council countries would be exposed to concentration levels of $PM_{2.5}$ above the WHO guidelines. However, in the MTFR-AC scenario, only 1% would be exposed to these concentrations. This decrease I equivalent to a change from 18 million people in the MTFR-AC scenario.”).

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

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

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

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

[390] Desch S. J., Smith N., Groppi C., Vargas P., Jackson R., Kalyaan A., Nguyen P., Probst L., Rubin M. E., Singleton H., Spacek A., Truitt A., Zaw P. P., & Hartnett H. E. (2017) *Arctic ice management*, EARTH'S FUTURE 5: 107–27, 107 ("Here we investigate a means for enhancing Arctic sea ice production by using wind power during the Arctic winter to pump water to the surface, where it will freeze more rapidly. We show that where appropriate devices are employed, it is possible to increase ice thickness above natural levels, by about 1 m over the course of the winter. We examine the effects this has in the Arctic climate, concluding that deployment over 10% of the Arctic, especially where ice survival is marginal, could more than reverse current trends of ice loss in the Arctic, using existing industrial capacity. We propose that winter ice thickening by wind-powered pumps be considered and assessed as part of a multipronged strategy for restoring sea ice and arresting the strongest feedbacks in the climate system."). *See also* Field L., Ivanova D., Bhattacharyya S., Mlaker V., Sholtz A., Decca R., Manzara A., Johnson D., Christodoulou E., Walter P., & Katuri K. (2018) *Increasing Arctic Sea Ice Albedo Using Localized Reversible Geoengineering*, EARTH'S FUTURE 6(6): 882–901 (discussing testing hollow silica beads to enhance albedo of Arctic sea ice); *and* Bodansky D. & Hunt H. (2020) *Arctic Climate Interventions*, INT. J. MAR. COAST. LAW 35(3): 596–617, 605–606 ("Arctic ice management focuses on saving Arctic ice directly, either by increasing the rate of freezing or by decreasing the rate of melting. One proposed technique to increase freezing would be to spray seawater directly on top of the ice during the Arctic winter, when despite global warming it is still generally very cold.[41] Ice is an insulator and slows the freezing of the water beneath it. Pumping water from under sea ice and spraying it on top, where it would be directly exposed to frigid air, would thus increase the rate of freezing and result in thicker ice… A second option focuses on decreasing the rate of melting of Arctic ice by spraying reflective beads on top of the ice in order to increase its albedo.[43]").

[391] Ocean Visions, *Repair: Exploring Interventions to Prolong Health of Critical Marine Ecosystems* (*last visited* 28 August 2023) ("We are in the process of developing a digital, interactive road map on Arctic sea ice preservation tools and strategies, adding to the suite of existing road maps on ocean-based climate solutions. The map will review the current state and potential of relevant technology pathways, social and environmental risks and co-benefits of such technologies, policy and governance considerations, and the knowledge gaps that need attention to further evaluate the tools and interventions. The map will also identify a set of first-order priorities for additional research, development, and potential testing. This road map is slated to be published in late 2023.").

[392] Canadell J. G., *et al.* (2021) *Chapter 5: Global Carbon and other Biogeochemical Cycles and Feedbacks*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), FAQ 5.1, 771 ("For decades, about half of the carbon dioxide (CO_2) that human activities have emitted to the atmosphere has been taken up by natural carbon sinks in vegetation, soils and oceans. These natural sinks of CO_2 have thus roughly halved the rate at which atmospheric CO_2 concentrations have increased, and therefore slowed down global warming. However, observations show that the processes underlying this uptake are beginning to respond to increasing CO_2 in the atmosphere and climate change in a way that will weaken nature's capacity to take up CO_2 in the future."). *See also* Joos F., *et al.* (2013) *Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: a multi-model analysis*, ATMOS. CHEM. PHYS. 13(5): 2793–2825, 2804 (Figure 1a); *and* Archer D., Eby M., Brovkin V., Ridgwell A., Cao L., Mikolajewicz U., Caldeira K., Matsumoto K., Munhoven G., Montenegro A., &

Tokos K. (2009) *Atmospheric Lifetime of Fossil Fuel Carbon Dioxide*, Annu. Rev. Earth Planet. Sci. 37: 117–134, 121 (“Finally, the 2007 IPCC report removed the table from the “Policymaker Summary,” and added in the “Executive Summary” of Chapter 7 on the carbon cycle, “About half of a CO_2 pulse to the atmosphere is removed over a timescale of 30 years; a further 30% is removed within a few centuries; and the remaining 20% will typically stay in the atmosphere for many thousands of years” (Denman et al 2007, page 501).”).

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

[394] Lovejoy T. E. & Nobre C. (2018) *Amazon’s Tipping Point*, Sci. Adv. 4(2): eaat2340, 1 (“We believe that negative synergies between deforestation, climate change, and widespread use of fire indicate a tipping point for the Amazon system to flip to nonforest ecosystems in eastern, southern and central Amazonia at 20–25% deforestation.”). *See also* Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, Rev. Geophys. 61(e2021RG000757): 1–81, 28 (“Ultimately, current research cannot eliminate the possibility that changes across the boreal zone due to a warming climate could act as a net positive climate feedback, thanks to the potential for permafrost thaw and wildfires to liberate the soil carbon that makes up the majority of stored carbon across this ecosystem. Consequently, boreal forest dieback and shifts represent one of the more potentially immediate and significant climate system tipping elements (Table 7).”).

[395] Griscom B. W., *et al.* (2017) *Natural climate solutions*, Proc. Nat’l. Acad. Sci. 114(44): 11645–11650, 11645 (“Better stewardship of land is needed to achieve the Paris Climate Agreement goal of holding warming to below 2 °C; however, confusion persists about the specific set of land stewardship options available and their mitigation potential. To address this, we identify and quantify “natural climate solutions” (NCS): 20 conservation, restoration, and improved land management actions that increase carbon storage and/or avoid greenhouse gas emissions across global forests, wetlands, grasslands, and agricultural lands. We find that the maximum potential of NCS—when constrained by food security, fiber security, and biodiversity conservation—is 23.8 petagrams of CO_2 equivalent ($PgCO_2e$) y^{-1} (95% CI 20.3–37.4). This is ≥30% higher than prior estimates, which did not include the full range of options and safeguards considered here. About half of this maximum (11.3 $PgCO_2e$ y^{-1}) represents cost-effective

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climate mitigation, assuming the social cost of CO_2 pollution is ≥100 USD $MgCO_2e^{-1}$ by 2030. Natural climate solutions can provide 37% of cost-effective CO_2 mitigation needed through 2030 for a >66% chance of holding warming to below 2 °C. One-third of this cost-effective NCS mitigation can be delivered at or below 10 USD $MgCO_2^{-1}$. Most NCS actions—if effectively implemented—also offer water filtration, flood buffering, soil health, biodiversity habitat, and enhanced climate resilience. Work remains to better constrain uncertainty of NCS mitigation estimates. Nevertheless, existing knowledge reported here provides a robust basis for immediate global action to improve ecosystem stewardship as a major solution to climate change."). *See also* Moomaw W. R., Masino S. A., & Faison E. K. (2019) *Intact Forests in the Unites States: Proforestation Mitigates Climate Change and Serves the Greatest Good*, Perspective, Front. For. Glob. Change 2(27): 1–10, 1 ("Climate change and loss of biodiversity are widely recognized as the foremost environmental challenges of our time. Forests annually sequester large quantities of atmospheric carbon dioxide (CO_2), and store carbon above and below ground for long periods of time. Intact forests—largely free from human intervention except primarily for trails and hazard removals—are the most carbon-dense and biodiverse terrestrial ecosystems, with additional benefits to society and the economy. … The recent *1.5 Degree Warming Report* by the Intergovernmental Panel on Climate Change identifies *reforestation* and *afforestation* as important strategies to increase negative emissions, but they face significant challenges: afforestation requires an enormous amount of additional land, and neither strategy can remove sufficient carbon by growing young trees during the critical next decade(s). In contrast, growing existing forests intact to their ecological potential—termed *proforestation*—is a more effective, immediate, and low-cost approach that could be mobilized across suitable forests of all types. Proforestation serves the greatest public good by maximizing co-benefits such as nature-based biological carbon sequestration and unparalleled ecosystem services such as biodiversity enhancement, water and air quality, flood and erosion control, public health benefits, low impact recreation, and scenic beauty."); *and* World Wildlife Fund (2020) *Living Planet Report 2020 – Bending the curve of biodiversity loss*, Almond R. E. A., Grooten M., & Petersen T. (eds.), 6 ("The global Living Planet Index continues to decline. It shows an average 68% decrease in population sizes of mammals, birds, amphibians, reptiles and fish between 1970 and 2016. … It matters because biodiversity is fundamental to human life on Earth, and the evidence is unequivocal – it is being destroyed by us at a rate unprecedented in history. Since the industrial revolution, human activities have increasingly destroyed and degraded forests, grasslands, wetlands and other important ecosystems, threatening human well-being. Seventy-five per cent of the Earth's ice-free land surface has already been significantly altered, most of the oceans are polluted, and more than 85% of the area of wetlands has been lost.").

[396] Bloomer L., Sun X., Dreyfus G., Ferris T., Zaelke D., & Schiff C. (2022) *A Call to Stop Burning Trees in the Name of Climate Mitigation*, Vt. J. Envt'l. Law 23: 94–123, 94 ("Burning trees for energy delivers a one-two punch against climate change mitigation efforts. Harvesting woody biomass reduces the sequestration potential of forest carbon sinks, while the combustion of woody biomass releases large quantities of carbon into the air.[1] Forest regrowth may not offset these emissions for many decades[2]—well beyond the time the world has left to slow warming to avoid catastrophic impacts from climate change."). *See also* Raven P., *et al.* (11 February 2021) *Letter Regarding Use of Forests for Bioenergy*, Woodwell Climate Research Center ("Trees are more valuable alive than dead both for climate and for biodiversity. To meet future net zero emission goals, your governments should work to preserve and restore forests and not to burn them.").

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

[398] Duffy K. A., Schwalm C. R., Arcus V. L., Koch G. W., Liang L. L., & Schipper L. A. (2021) *How close are we to the temperature tipping point of the terrestrial biosphere?*, Sci. Adv. 7(3): 1–8, 1 ("The temperature dependence of global photosynthesis and respiration determine land carbon sink strength. While the land sink currently mitigates ~30% of anthropogenic carbon emissions, it is unclear whether this ecosystem service will persist and, more

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specifically, what hard temperature limits, if any, regulate carbon uptake. Here, we use the largest continuous carbon flux monitoring network to construct the first observationally derived temperature response curves for global land carbon uptake. We show that the mean temperature of the warmest quarter (3-month period) passed the thermal maximum for photosynthesis during the past decade. At higher temperatures, respiration rates continue to rise in contrast to sharply declining rates of photosynthesis. Under business-as-usual emissions, this divergence elicits a near halving of the land sink strength by as early as 2040."). *See also* Hubau W., *et al.* (2020) *Asynchronous carbon sink saturation in African and Amazonian tropical forests*, NATURE 579: 80–87, 85 ("In summary, our results indicate that although intact tropical forests remain major stores of carbon and are key centres of biodiversity11, their ability to sequester additional carbon in trees is waning. In the 1990s intact tropical forests removed 17% of anthropogenic CO_2 emissions. This declined to an estimated 6% in the 2010s, because the pan-tropical weighted average per unit area sink strength declined by 33%, forest area decreased by 19% and anthropogenic CO_2 emissions increased by 46%. Although tropical forests are more immediately threatened by deforestation46 and degradation47, and the future carbon balance will also depend on secondary forest dynamics48 and forest restoration plans49, our analyses show that they are also affected by atmospheric chemistry and climatic changes. Given that the intact tropical forest carbon sink is set to end sooner than even the most pessimistic climate driven vegetation models predict4,5, our analyses suggest that climate change impacts in the tropics may become more severe than predicted. Furthermore, the carbon balance of intact tropical forests will only stabilize once CO_2 concentrations and the climate stabilizes."); *and* Intergovernmental Panel on Climate Change (2021) *Summary for Policymakers*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 20 ("Based on model projections, under the intermediate scenario that stabilizes atmospheric CO_2 concentrations this century (SSP2-4.5), the rates of CO_2 taken up by the land and oceans are projected to decrease in the second half of the 21st century (*high confidence*). Under the very low and low GHG emissions scenarios (SSP1-1.9, SSP1-2.6), where CO_2 concentrations peak and decline during the 21st century, land and oceans begin to take up less carbon in response to declining atmospheric CO_2 concentrations (*high confidence*) and turn into a weak net source by 2100 under SSP1-1.9 (*medium confidence*). It is very unlikely that the combined global land and ocean sink will turn into a source by 2100 under scenarios without net negative emissions32 (SSP2-4.5, SSP3-7.0, SSP5-8.5). … Additional ecosystem responses to warming not yet fully included in climate models, such as CO_2 and CH_4 fluxes from wetlands, permafrost thaw and wildfires, would further increase concentrations of these gases in the atmosphere (*high confidence*).").

[399] Duffy K. A., Schwalm C. R., Arcus V. L., Koch G. W., Liang L. L., & Schipper L. A. (2021) *How close are we to the temperature tipping point of the terrestrial biosphere?*, SCI. ADV. 7(3): 1–8, 3 ("This…calls into question the future viability of the land sink, along with Intended Nationally Determined Contributions (INDCs) within the Paris Climate Accord, as these rely heavily on land uptake of carbon to meet pledges. In contrast to Representative Concentration Pathway 8.5 (RCP8.5), warming associated with scenario RCP2.6 could allow for near-current levels of biosphere productivity, preserving the majority land carbon uptake (~10 to 30% loss)."). *See also* Rockström J., Beringer T., Hole D., Griscom B., Mascia M. B., Folke C., & Creutzig F. (2021) *We Need Biosphere Stewardship That Protects Carbon Sinks and Builds Resilience*, PROC. NAT'L. ACAD. SCI. 118(38): 1–8, 1–2 ("All major global climate models whose simulations give us hope of meeting the target of the Paris Climate Agreement—to keep warming well below 2 °C—take the continued provision of this gigantic biosphere endowment for granted, merely concluding, as in the recent IPCC report, that the efficiency of nature's carbon sink may reduce slightly for high emission pathways. This means that the ability of intact nature to continue to sequester carbon is already factored into the climate models and thus in the estimate of the remaining carbon budget to hold to the Paris climate target. Yet this fundamental assumption relies on terrestrial and marine ecosystems remaining sufficiently intact and resilient to human pressures, even as climate change progresses (3). It is therefore concerning that the IPCC now concludes that Earth's temperature is slightly more sensitive to rising CO_2 concentrations than previously thought (4)—meaning our remaining carbon budget to achieve the Paris target may have effectively shrunk. If we were able to more accurately simulate feedbacks in the global carbon cycle, such as tipping points in forest ecosystems (5) and abrupt permafrost thaw (6), the estimated remaining budget could disappear altogether.").

[400] Canadell J. G., *et al.* (2021) *Chapter 5: Global Carbon and other Biogeochemical Cycles and Feedbacks*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), Table 5.6, 5-740 ("To

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

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

[402] Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, REV. GEOPHYS. 61: 1–81, 24 ("Between the biomass in soil, permafrost, and living and dead vegetation, boreal forests represent a significant pool of terrestrial organic carbon (30% of global soil carbon) (Mcguire et al., 2009; Turetsky et al., 2019), and constitute 30% of global forest area (Kasischke, 2000). Of this fraction, two-thirds of boreal forest are found within Russia, with Russia's boreal forests estimated to contribute around half (0.6 Gt C/yr) of the total global terrestrial carbon sink (Dolman et al., 2012; Schaphoff et al., 2013). Recent research has proposed that boreal forest carbon stocks could be underestimated, with updated calculations suggesting that boreal regions hold more terrestrial carbon (Bradshaw & Warkentin, 2015) than tropical areas, which have been previously suggested to harbor the largest stock of carbon among all terrestrial biomes (Y. Pan et al., 2011).").

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

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

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

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

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

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

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

[410] Sedano F. & Randerson J. T. (2014) *Multi-scale influence of vapor pressure deficit on fire ignition and spread in boreal forest ecosystems*, BIOGEOSCI. 11(14): 3739–3755, 3750 ("We found strong positive relationships between VPD and burned area at different temporal and spatial scales. This relationship was observed at a fine temporal resolution (daily VPD versus daily burned area) for individual fires, at a regional level within a single fire season, and across different years for the study domain as a whole. VPD also was implicated as an important climate regulator during multiple fire stages including, specifically, the probability that a lightning strike triggered ignition, during periods of initial fire spread, for daily burned area variations in larger fires, and the timing of fire extinction."). *See also* Clarke H., Nolan R. H., De Dios V. R., Bradstock R., Griebel A., Khanal S., & Boer M. M. (2022) *Forest fire threatens global carbon sinks and population centres under rising atmospheric water demand*, NAT. COMMUN. 13: 1–10, 3 ("We found that for many forested regions, and for the majority of global burned area in forests, the probability of fire occurrence can be accurately predicted on the basis of exceedance of thresholds in daily maximum VPD. We also found that the value of these thresholds varied predictably across major forest types, being highest in tropical and subtropical forests and lowest in temperate and boreal forests.").

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

[412] Qiao L., Zuo Z., Zhang R., Piao S., Xiao D., & Zhang K. (2023) *Soil moisture–atmosphere coupling accelerates global warming*, NAT. COMMUN. 14(4908): 1–10, 2–3 ("Clearly, the uptrend of SA-induced warming associated with

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very high greenhouse gases emission would accelerate the speed of global warming, and the magnitude of acceleration would increase with time. Therefore, we posit that, unless we take early action to reduce emission, SA- and GHG-induced warming would become closely coupled, resulting in a positive feedback that may hasten the approach of distinct climate range. Should the most stringent emission pathway be adopted, our results suggest SA-induced warming will weaken significantly (Fig. 2a).").

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

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

[415] Wang S., Foster A., Lenz E. A., Kessler J. D., Stroeve J. C., Anderson L. O., Turetsky M., Betts R., Zou S., Liu W., Boos W. R., & Hausfather Z. (2023) *Mechanisms and Impacts of Earth System Tipping Elements*, REV. GEOPHYS. 61: 1–81, 26 ("Yet while boreal forest productivity and tree cover are on the decline at the southern edge of the boreal zone and within interior regions, 30-year data sets of satellite and observational evidence also point toward ongoing expansion of boreal forests northwards into area previously occupied by tundra thanks to higher temperatures (Figure 9) (Beck, Juday, et al., 2011; Ju & Masek, 2016; Pastick et al., 2019; Pearson et al., 2013). Since 1960, the growing season across the boreal zone has lengthened by 3 days/decade (Euskirchen et al., 2006). Expansion of trees into the tundra biome has implications for regional and global climate, as the albedo of forests is lower than that of tundra, leading to warmer winter conditions with greater tree cover (Bonan et al., 1992).").

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

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across this ecosystem. Consequently, boreal forest dieback and shifts represent one of the more potentially immediate and significant climate system tipping elements (Table 7).”).

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

[418] Taylor L. (5 September 2022) *The Amazon rainforest has already reached a crucial tipping point,* New Scientist (“Marlene Quintanilla at the Amazon Geo-Referenced Socio-Environmental Information Network (RAISG) and her colleagues, working in partnership with various groups, including the Coordinator of Indigenous Organizations of the Amazon River Basin, used forest coverage data to map how much of the Amazon was lost between 1985 and 2020 and also looked at forest density, rainfall patterns and carbon storage. …The report finds that 33 per cent of the Amazon remains pristine and 41 per cent of areas have low degradation and could restore themselves. But 26 per cent of areas have been found to have gone too far to restore themselves: 20 per cent is lost entirely and 6 per cent is highly degraded and would need human support to be restored.”). *See also* Lenton T. M., Rockstrom J., Gaffney O., Rahmstorf S., Richardson K., Steffen W., & Schellnhuber H. J. (2019) *Climate tipping points—too risky to bet against*, Comment, Nature 575: 592–595, 593 (“Estimates of where an Amazon tipping point could lie range from 40% deforestation to just 30% forest-cover loss. About 17% has been lost since 1970. The rate of deforestation varies with changes in policy. Finding the tipping point requires models that include deforestation and climate change as interacting drivers, and that incorporate fire and climate feedbacks as interacting tipping mechanisms across scales.”).

[419] Douville H., *et al.* (2021) *Chapter 8: Water Cycle Changes*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 1149 (“Both deforestation and drying are projected to increase by 2100, resulting in a worst-case scenario of up to a 50% loss in forest cover by 2050 (Soares-Filho et al., 2006; Boisier et al., 2015; Steege et 50 al., 2015; Gomes et al., 2019).”).

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

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

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

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

[424] Goldstein A., Noon M. L., Ledezma J. C., Roehrdanz P. R., Raghav S., McGreevey M., Stone C., Shrestha S., Golden Kroner R., Hole D., & Turner W. (2021) IRRECOVERABLE CARBON: THE PLACES WE MUST PROTECT TO AVERT CLIMATE CATASTROPHE, Conservation International, 7 ("'Irrecoverable carbon' refers to the vast stores of carbon in nature that are vulnerable to release from human activity and, if lost, could not be restored by 2050 — when the world must reach net-zero emissions to avoid the worst impacts of climate change … There are high concentrations of irrecoverable carbon in the Amazon (31.5 Gt), the Congo Basin (8.1 Gt), and New Guinea (7.3 Gt). Other important irrecoverable carbon reserves are located in the Pacific Northwest of North America, the Valdivian forests of Chile, the mangroves and swamp forests of Guyana, the peatlands of Northern Scotland, Niger Delta's mangroves,

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Cambodia's Tonle Sap Lake, the Scandinavian and Siberian boreal forests, and the eucalyptus forest of Southeast Australia, among others."). *See also* Goldstein A., *et al.* (2020) *Protecting irrecoverable carbon in Earth's ecosystems*, NAT. CLIM. CHANGE 10(4): 287–295; *and* Noon M. L., Goldstein A., Ledezma J. C., Roehrdanz P. R., Cook-Patton S. C., Spawn-Lee S. A., Wright T. M., Gonzalez-Roglich M., Hole D. G., Rockström J., & Turner W. R. (2021) *Mapping the irrecoverable carbon in Earth's ecosystems*, NAT. SUSTAIN. 5: 37–46.

[425] Girardin C. A. J., Jenkins S., Seddon N., Allen M., Lewis S. L., Wheeler C. E., Griscom B. W., & Malhi Y. (2021) *Nature-based solutions can help cool the planet — if we act now*, Comment, NATURE 593: 191–194, 192 ("A subset of nature-based solutions can be used specifically to limit warming. These 'natural climate solutions' aim to reduce atmospheric greenhouse-gas concentrations in three ways. One is to avoid emissions by protecting ecosystems and thus reducing carbon release; this includes efforts to limit deforestation. Another is to restore ecosystems, such as wetlands, so that they sequester carbon. The third is to improve land management — for timber, crops and grazing — to reduce emissions of carbon, methane and nitrous oxide, as well as to sequester carbon (see 'Three steps to natural cooling').").

[426] Moomaw W. R., Masino S. A., & Faison E. K. (2019) *Intact Forests in the United States: Proforestation Mitigates Climate Change and Serves the Greatest Good*, FRONT. FOR. GLOB. CHANGE 2(27): 1–10, 1 ("The recent *1.5 Degree Warming Report* by the Intergovernmental Panel on Climate Change identifies *reforestation* and *afforestation* as important strategies to increase negative emissions, but they face significant challenges: afforestation requires an enormous amount of additional land, and neither strategy can remove sufficient carbon by growing young trees during the critical next decade(s). In contrast, growing existing forests intact to their ecological potential—termed *proforestation*—is a more effective, immediate, and low-cost approach that could be mobilized across suitable forests of all types. Proforestation serves the greatest public good by maximizing co-benefits such as nature-based biological carbon sequestration and unparalleled ecosystem services such as biodiversity enhancement, water and air quality, flood and erosion control, public health benefits, low impact recreation, and scenic beauty.").

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

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

[429] Booth M. S. (2018) *Not Carbon Neutral: Assessing the Net Emissions Impact of Residues Burned for Bioenergy*, ENVIRON. RES. LETT. 13(3): 1–10, 8 ("For bioenergy to offer genuine climate mitigation, it is essential to move beyond

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the assumption of instantaneous carbon neutrality. The [net emissions impact (NEI)] approach provides a simple means to estimate net bioenergy emissions over time, albeit one that tends to underestimate actual impacts. The model finds that for plants burning locally sourced wood residues, from 41% (extremely rapid decomposition) to 95% (very slow decomposition) of cumulative direct emissions should be counted as contributing to atmospheric carbon loading by year 10. Even by year 50 and beyond, the model shows that net emissions are a significant proportion of direct emissions for many fuels.”). *See also* Sterman J. D., Siegel L., & Rooney-Varga J. N. (2018) *Does Replacing Coal with Wood Lower CO_2 Emissions? Dynamic Lifecycle Analysis of Wood Bioenergy*, Environ. Res. Lett. 13(015007): 1–10, 6 (“Scenario 2 shows the realistic case with the combustion efficiency and supply chain emissions estimated for wood pellets (supplementary table S5), again assuming 25% of the biomass is harvested by thinning. Because production and combustion of wood generate more CO_2 than coal, the first impact of bioenergy use is an increase in atmospheric CO_2. Regrowth gradually transfers C from the atmosphere to biomass and soil C stocks, leading to a carbon debt payback time of 52 years; after 100 years CO_2 remains 62% above the zero C case.”); *and* Bloomer L., Sun X., Dreyfus G., Ferris T., Zaelke D., & Schiff C. (2022) *A Call to Stop Burning Trees in the Name of Climate Mitigation*, Vt. J. Envtl. Law 23: 94–123.

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

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

[432] The White House (2021) Plan to Conserve Global Forests: Critical Carbon Sinks, *discussed in* United States Department of State (3 November 2021) *Plan to Conserve Global Forests: Critical Carbon Sinks*, Fact Sheet (“At COP26 during the World Leaders Summit Forest Day session on November 2, 2021, the United States announced the **Plan to Conserve Global Forests: Critical Carbon Sinks**. This decade-long, whole-of-government Plan sets forth the U.S. approach to conserving critical global terrestrial carbon sinks, deploying a range of diplomatic, policy, and financing tools. The first-of-its-kind plan for the U.S. government seeks to catalyze the global effort to conserve and restore the forests and other ecosystems that serve as critical carbon sinks. Subject to Congressional appropriations, by 2030, the United States intends to dedicate up to $9 billion of our international climate funding to support the objectives of the Plan.… The Plan supports collective goals the United States has previously endorsed, including efforts to end natural forest loss by 2030; to significantly increase the rate of global restoration of degraded landscapes and forestlands; and to slow, halt, and reverse forest cover and carbon loss. The Plan outlines the initial approaches the United States intends to deploy to achieve four key objectives: Incentivize forest and ecosystem conservation and forest landscape restoration; Catalyze private sector investment, finance, and action to conserve critical carbon sinks; Build long-term capacity and support the data and monitoring systems that enhance accountability; Increase ambition for climate and conservation action.”).

[433] Müller J. D., Gruber N., Carter B., Feely R., Ishii M., Lange N., Lauvset S. K., Murata A., Olsen A., Pérez F. F., Sabine C., Tanhua T., Wanninkhof R., & Zhu D. (2023) *Decadal Trends in the Oceanic Storage of Anthropogenic Carbon From 1994 to 2014*, AGU Adv. 4(4): 1–28, 1–2 (“Models and observation-based estimates agree that since the beginning of the industrial period, the ocean has taken up roughly 30% of the total human CO_2 emissions due to

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fossil fuel combustion, cement production, and land use change (Crisp et al., 2022; Friedlingstein et al., 2022; Gruber et al., 2019; Khatiwala et al., 2009, 2013; Sabine et al., 2004).").

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

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

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

[437] Nzotungicimpaye C. M., MacIsaac A. J., & Zickfeld K. (2023) *Delaying methane mitigation increases the risk of breaching the 2 °C warming limit*, COMMUN. EARTH. ENVIRON. 4(250): 1–8, 4 ("While anthropogenic CH_4 emissions

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

[438] U.S. National Academies of Sciences, Engineering, and Medicine, *Atmospheric Methane Removal: Development of a Research Agenda* (*last visited* 28 August 2023).

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

[440] Wanser K., Wong A., Karspeck A., & Esguerra N. (2023) *NEAR-TERM CLIMATE RISK AND INTERVENTION: A ROADMAP FOR RESEARCH, U.S. RESEARCH INVESTMENT, AND INTERNATIONAL SCIENTIFIC COOPERATION*, SilverLining, 40 (“As the essential foundation for any forward path, the global community must aggressively reduce GHG emissions. Today, this should include heightened focus on reducing emissions of substances with the potential for greatest reduction in warming in the near term (e.g., methane, nitrous oxide). Due to the high levels of GHGs already in the atmosphere, society must also aggressively remove GHGs. To do this effectively requires a portfolio that considers the speed, scalability, duration, and ecological impacts of various approaches.”).

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

Reducing emissions of methane, which has a high greenhouse gas warming potential, will ameliorate climate change.”).

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

[443] Advanced Research Projects Agency-Energy (2 December 2021) *U.S. Department of Energy Awards $35 Million for Technologies to Reduce Methane Emissions*, Press Release (“MAHLE Powertrain (Plymouth, MI) will develop a catalytic system to oxidize methane in the exhaust gas of lean-burn natural gas fired engines. (Selection amount: $3,257,089). … Johnson Matthey, Inc. (Wayne, PA) is developing new technology, which uses a noble metal catalyst to combust the dilute methane in coal mine ventilation systems. (Selection amount: $4,346,015) Massachusetts Institute of Technology (Cambridge, MA) is developing a low-cost copper-based catalyst for reducing methane emissions. (Selection amount: $2,020,903)….”). *See also* Advanced Research Projects Agency-Energy (2 December 2021) *REMEDY—Reducing Emissions of Methane Every Day of the Year: Project Descriptions*, Press Release.

[444] Alicat Scientific, *Frost Methane mitigates methane gas emissions from Arctic Circle permafrost* (*last visited* 13 June 2023) (“Frost Methane and collaborators from University of Alaska Fairbanks tested their methane-capture technology for the first time on August 13, 2021. The team deployed their equipment at a lake in the Arctic Circle, about 67.25 degrees north. Laughlin Barker, Frost Methane’s Senior Embedded Systems Engineer, described the lake as, ‘basically a Jacuzzi, there’s so much natural gas.’”).

[445] de Richter R., *et al*. (11 September 2019) *Iron Salt Aerosol a natural method to remove methane & other greenhouse gases*, Institution of Mechanical Engineers Presentation, 8 (“Iron Salt Aerosol can enhance both natural sinks: the hydroxyl radical sink and the chlorine sink.”). *See also* Canadell J. G., *et al.* (2021) *Chapter 5: Global Carbon and other Biogeochemical Cycles and Feedbacks*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 701 (“About 90% of the loss of atmospheric CH_4 occurs in the troposphere by reaction with hydroxyl (OH) radical, 5% by bacterial soil oxidation, and the rest 5% by chemical reactions with OH, excited state oxygen (O^1D), and atomic chlorine (Cl) in the stratosphere (Saunois et al., 2020).”); *and* Lan X., Nisbet E. G., Dlugokencky E. J., & Michel S. E. (2021) *What do we know about the global methane budget? Results from four decades of atmospheric CH_4 observations and the way forward*, PHIL. TRANS. R. SOC. A 379(2210): 1–14, 8 (“The largest atmospheric loss process in the global CH_4 budget is mostly initiated by reaction with OH, especially in the tropical mid-troposphere, but also by Cl and $O(^1D)$ (stratosphere only). Oxidation by microbes in soils is likely a small sink, but uncertainty in its magnitude and trend remain large [37].).

[446] van Herpen M. M. J. W., Li Q., Saiz-Lopez A., Liisberg J. B., Röckmann T., Cuevas C. A., Fernandez R. P., Mak J. E., Mahowald N. M., Hess P., Meidan D., Stuut J.-B. W., & Johnson M. S. (2023) *Photocatalytic chlorine atom production on mineral dust–sea spray aerosols over the North Atlantic,* PROC. NATL. ACAD. SCI. 120(31): 1–8, 2, 5 (“Here, we present field and modeling evidence of the mechanism of the production of atomic Cl via the photocatalytic oxidation of chloride in aerosols containing Sahara mineral dust. By this mechanism, Cl_2 and Cl are generated when lofted iron-bearing mineral dust aerosol from North Africa descends into the marine boundary layer (MBL) over the Atlantic and mixes with sea spray aerosol to form Mineral Dust-Sea spray Aerosols (MDSA). We combine data from field with global atmospheric modeling and predict extremely low δ^{13}C-CO values that match those seen in CO in air samples from Barbados (25); these results remained unexplained for 20 y. Finally, we discuss the global significance of this mechanism that is not yet included in global models…. Our model showed that Cl from mineral dust/salt aerosols increases CH_4 loss via Cl by 4.8 Tg y^{-1} globally (0.9% of total CH_4 loss).”).

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[447] Li Q., Meidan D., Hess P., Añel J. A., Cuevas C. A., Doney S., Fernandez R. P., van Herpen M., Höglund-Isaksson L., Johnson M. S., Kinnison D. E., Lamarque J.-F., Röckmann T., Mahowald N. M., & Saiz-Lopez A. (2023) *Global environmental implications of atmospheric methane removal through chlorine-mediated chemistry-climate interactions*, NAT. COMMUN. 14(4045): 1–10, 2 ("The atmospheric response to the additional chlorine emissions (Methods) is highly complex and nonlinear (Fig. 1). Based on our CESM modeling results, adding 90 Tg Cl/year (S90; Table S1) can be regarded as an important threshold for the response of CH_4 to chlorine changes. This is comparable to tripling the current-day chlorine atom burden (Fig. S2). Below this threshold, increases in tropospheric chlorine emissions (S10 scenario) from RCP8.5 first lead to an increase in the atmospheric CH_4 burden compared to RCP8.5 in 2030; the emission scenarios of S40, S60, and S80 result in approximately the same CH_4 burden and lifetime as S10 (Fig. 1 inset). Such an increase in methane lifetime is due to an increase in global chlorine burden as was previously shown by Horowitz et al.12. Here we note that above this emission threshold of 90 Tg Cl/year, the global CH_4 burden begins to decrease.").

[448] In the U.S., the Consolidated Appropriations Act of 2022 and Investment and Innovation and Jobs Act of 2021 allocated $49 million of funding per year to the Department of Energy for CDR technology and a $3.5 billion investment in four direct air capture hubs, which is expected to remove a million tonnes of CO_2 a year. Additionally, the CHIPS and Science Act of 2022 included several provisions relating to carbon dioxide removal, including $1 billion in funding for carbon removal research and development, establishing a Basic Energy Science Program to research carbon conversion and sequestration in geologic formations, and creating "at least two" carbon storage research centers. *See* Consolidated Appropriations Act, Pub. L. No. 117-103, 136 Stat. 222-227 (2022); Infrastructure Investment and Jobs Act, Pub. L. No. 117-58, § 40308 (2021) (codified at 42 U.S.C. § 16371); *and* CHIPS and Science Act, Pub. L. No. 117-167, §§ 10102, 10771 (2022).

[449] A Swiss company, Climeworks, deployed the world's largest direct air capture and storage plant for carbon dioxide, where they work with the Icelandic start-up Carbfix to store carbon by injecting the carbon into subsurface ground, where it reacts with rock formations to turn into rocks within two years. *See* Climeworks, *Carbon dioxide removal: our service to fight global warming* (*last visited* 14 June 2023) ("At Climeworks, we offer carbon dioxide removal for individuals and businesses who want to fight climate change. With our service, you can take action on behalf of the planet by permanently removing your unavoidable CO_2 emissions. To achieve this, we combine our direct air capture technology with permanent underground storage (direct air capture & storage = DAC+S). Direct air capture, as the term implies, is a technology that captures carbon dioxide directly from the air — such as our Orca facility in Hellisheidi, Iceland. Permanent underground storage is what happens after we hand the air-captured CO_2 over to our storage partner — Carbfix. They transport the CO_2 deep underground, where it reacts with basalt rock through a natural process, transforms into stone, and remains for over 10,000 years. This makes our carbon dioxide removal service both effective and permanent."); *and* Carbfix, *How it works* (*last visited* 14 June 2023) ("Trees and vegetation are not the only form of carbon drawdown from the atmosphere. Vast quantities of carbon are naturally stored in rocks. Carbfix imitates and accelerates these natural processes, where carbon dioxide is dissolved in water and interacts with reactive rock formations, such as basalts, to form stable minerals providing a permanent and safe carbon sink. The Carbfix process captures and permanently removes CO_2. The technology provides a complete carbon capture and injection solution, where CO_2 dissolved in water – a sparkling water of sorts – is injected into the subsurface where it reacts with favorable rock formations to form solid carbonate minerals via natural processes in about 2 years. For the Carbfix technology to work, one needs to meet three requirements: favorable rocks, water, and a source of carbon dioxide."), *discussed in* Rawnsley J. (11 August 2022) *Racing against the clock to decarbonise the planet*, FINANCIAL TIMES. For a discussion on carbon dioxide storage through a mineral carbonation process, *see* Snæbjörnsdóttir S. Ó., Sigfússon B., Marieni C., Goldberg D., Gislason S. R., & Oelkers E. H. (2020) *Carbon dioxide storage through mineral carbonation*, NAT. REV. EARTH ENVIRON. 1: 90–102; Galeczka I. M., Stefánsson A., Kleine B. I., Gunnarsson-Robin J., Snæbjörnsdóttir S. Ó., Sigfússon B., Gunnarsdóttir S. H., Weisenberger T. B., & Oelkers E. H. (2022) *A pre-injection assessment of CO_2 and H_2S mineralization reactions at the Nesjavellir (Iceland) geothermal storage site*, INT. J. GREENH. GAS CONTROL 115(103610): 1–18; *and* Ratouis T., Snæbjörnsdóttir S. Ó., Voigt M. J., Sigfússon B., Aradóttir E. A., & Hjörleifsdóttir V. (2022) *A transport model of long-term CO_2 and H_2S injection into basaltic rocks at Hellisheidi, SW-Iceland*, INT. J. GREENH. GAS CONTROL 114(103586): 1–20. In July 2022, Carbfix was awarded 16 billion Icelandic Króna (US $116 million) by the European Union's Innovation Fund to build the

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Coda Terminal Plant, which could store up to 3 million tonnes of CO_2 annually by 2031. *See also* Carbfix (11 July 2022) *Carbfix's Coda Terminal awarded large EU grant* ("Carbfix has been selected for grant award from the European Innovation Fund to build the Coda Terminal, a large-scale CO_2 transport and storage hub at Straumsvík, Iceland. The hub will be the first of its kind in the world. Operations are set to commence in mid-2026 and full capacity will be achieved in 2031, when up to 3 million tons of CO_2 will be annually stored by permanently mineralizing it underground."); *and* European Commission (12 July 2022) *Innovation Fund: EU invests €1.8 billion in clean tech projects*,* Press Release ("Today, the EU is investing over €1.8 billion in 17 large-scale innovative clean-tech projects with a third round of awards under the Innovation Fund. Grants will be disbursed from the Innovation Fund to help bring breakthrough technologies to the market in energy-intensive industries, hydrogen, renewable energy, carbon capture and storage infrastructure, and manufacturing of key components for energy storage and renewables…. A project in Iceland will build a highly scalable onshore carbon mineral storage terminal with an estimated overall storage capacity of 880 million tonnes of CO_2."), *discussed in* (21 July 2022) *Carbfix gets the biggest EU grant any Icelandic company has been awarded*, ICELAND MONITOR.

[450] International Energy Agency (2022) *Direct Air Capture* ("Eighteen DAC plants are currently operational in Europe, the United States and Canada. All of these plants are small scale, and the large majority of them capture CO2 for utilisation – for drinks carbonation, for instance – with only two plants storing the captured CO2 in geological formations for removal. Only a few commercial agreements are in place to sell or store the captured CO2, while the remaining plants are operated for testing and demonstration purposes. The first large-scale DAC plant of up to 1 Mt CO_2/year is in advanced development and is expected to be operating in the United States by the mid-2020s. An improved investment environment led to announcements of several new DAC projects in 2021, including the Storegga Dreamcatcher Project (United Kingdom; aimed at carbon removal) and the HIF Haru Oni eFuels Pilot Plant (Chile; producing synthetic fuels from electrolysis-based hydrogen and air-captured CO_2). Synthetic fuels (up to 3 million litres) are also set to be produced by the Norsk e-Fuel AS consortium in Norway by 2024, including (but not using exclusively) CO_2 captured from DAC. In June 2022 1PointFive and Carbon Engineering announced plans to deploy 70 large-scale DAC facilities by 2035 (each with a capture capacity of up to 1 million tonnes per year) under current policy and voluntary and compliance market conditions, while Climeworks announced the construction of their largest plant to date, Mammoth (capture capacity up to 36 000 t CO_2/year), which should become operational by 2024."). *See also* Cross J. N., Sweeney C., Jewett E. B., Feely R. A., McElhany P., Carter B., Stein T., Kitch G. D., & Gledhill D. K. (2023) STRATEGY FOR NOAA CARBON DIOXIDE REMOVAL RESEARCH: A WHITE PAPER DOCUMENTING A POTENTIAL NOAA CDR SCIENCE STRATEGY AS AN ELEMENT OF NOAA'S CLIMATE INTERVENTIONS PORTFOLIO, National Oceanic and Atmospheric Administration Special Report.

[451] Wunderling N., Winkelmann R., Rockström J., Loriani S., Armstrong-McKay D., Ritchie P., Sakschewski B., & Donges J. (2023) *Global warming overshoots increase risks of climate tipping cascades in a network model*, NAT. CLIM. CHANG. 13: 75–82, 78–79 ("We define a high climate-risk zone as the region where the likelihood for no tipping event is smaller than 66% or the risk that one or more elements tip is higher than 33%. We compute this risk and find a marked increase for increasing convergence temperatures (compare Fig. 3d–f). For convergence temperatures of 1.5 °C and above, our results indicate that the high climate-risk zone spans the entire state space for final convergence temperatures of 1.5–2.0 °C. Only if final convergence temperatures are limited to or, better, below today's levels of global warming, while peak temperatures are below 3.0 °C, the tipping risks remain below 33% (Fig. 3d)…In the worst case of a convergence temperature of 2.0 °C (Fig. 3f), the tipping risk for at least one tipping event to occur is on the order of above 90% if peak temperatures of 4.0 °C are not prevented. The devastating negative consequences of such a scenario with high likelihood of triggering tipping events would entail notable sea-level rise, biosphere degradation or considerable North Atlantic temperature drops.").

[452] Dreyfus G. B., Xu Y., Shindell D., Zaelke D., & Ramanathan V. (2022) *Mitigating climate disruption in time: A self-consistent approach for avoiding both near-term and long-term global warming*, PROC. NAT'L. ACAD. SCI. 119(22): 1–8, 1 ("We find that mitigation measures that target only decarbonization are essential for strong long-term cooling but can result in weak near-term warming (due to unmasking the cooling effect of co-emitted aerosols) and lead to temperatures exceeding 2°C before 2050. In contrast, pairing decarbonization with additional mitigation measures targeting short-lived climate pollutants (SLCPs) and N_2O, slows the rate of warming a decade or two earlier than decarbonization alone and avoids the 2°C threshold altogether. These non-CO_2 targeted measures when combined

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with decarbonization can provide net cooling by 2030, reduce the rate of warming from 2030 to 2050 by about 50%, roughly half of which comes from methane, significantly larger than decarbonization alone over this timeframe.”).

[453] Armstrong McKay D. I., Staal A., Abrams J. F., Winkelmann R., Sakschewski B., Loriani S., Fetzer I., Cornell S. E., Rockström J., & Lenton T. M. (2022) *Exceeding 1.5°C global warming could trigger multiple climate tipping points*, Science 377(6611): 1–10, 7 (“The chance of triggering CTPs is already non-negligible and will grow even with stringent climate mitigation (SSP1-1.9 in Fig. 2, B and C). Nevertheless, achieving the Paris Agreement’s aim to pursue efforts to limit warming to 1.5°C would clearly be safer than keeping global warming below 2°C (90) (Fig. 2). Going from 1.5 to 2°C increases the likelihood of committing to WAIS and GrIS collapse near complete warm-water coral die-off, and abrupt permafrost thaw; further, the best estimate threshold for LABC collapse is crossed. The likelihood of triggering AMOC collapse, Boreal forest shifts, and extra-polar glacier loss becomes non-negligible at >1.5°C and glacier loss becomes likely by ~2°C. A cluster of abrupt shifts occur in ESMs at 1.5 to 2°C (19). Although not tipping elements, ASSI loss could become regular by 2°C, gradual permafrost thaw would likely become widespread beyond 1.5°C, and land carbon sink weakening would become significant by 2°C.”). *See also* Lenton T. M., Rockstrom J., Gaffney O., Rahmstorf S., Richardson K., Steffen W., & Schellnhuber H. J. (2019) *Climate tipping points—too risky to bet against*, Comment, Nature 575(7784): 592–595, 594 (“In our view, the clearest emergency would be if we were approaching a global cascade of tipping points that led to a new, less habitable, ‘hothouse’ climate state[11]. Interactions could happen through ocean and atmospheric circulation or through feedbacks that increase greenhouse-gas levels and global temperature. Alternatively, strong cloud feedbacks could cause a global tipping point[12,13].We argue that cascading effects might be common. Research last year[14] analysed 30 types of regime shift spanning physical climate and ecological systems, from collapse of the West Antarctic ice sheet to a switch from rainforest to savanna. This indicated that exceeding tipping points in one system can increase the risk of crossing them in others. Such links were found for 45% of possible interactions[14]. In our view, examples are starting to be observed. … If damaging tipping cascades can occur and a global tipping point cannot be ruled out, then this is an existential threat to civilization. No amount of economic cost–benefit analysis is going to help us. We need to change our approach to the climate problem. … In our view, the evidence from tipping points alone suggests that we are in a state of planetary emergency: both the risk and urgency of the situation are acute….”); Steffen W., *et al.* (2018) *Trajectories of the Earth System in the Anthropocene*, Proc. Nat’l. Acad. Sci. 115(33): 8252–8259, 8254 (“This analysis implies that, even if the Paris Accord target of a 1.5 °C to 2.0 °C rise in temperature is met, we cannot exclude the risk that a cascade of feedbacks could push the Earth System irreversibly onto a “Hothouse Earth” pathway. The challenge that humanity faces is to create a “Stabilized Earth” pathway that steers the Earth System away from its current trajectory toward the threshold beyond which is Hothouse Earth (Fig. 2). The human-created Stabilized Earth pathway leads to a basin of attraction that is not likely to exist in the Earth System’s stability landscape without human stewardship to create and maintain it. Creating such a pathway and basin of attraction requires a fundamental change in the role of humans on the planet. This stewardship role requires deliberate and sustained action to become an integral, adaptive part of Earth System dynamics, creating feedbacks that keep the system on a Stabilized Earth pathway (Alternative Stabilized Earth Pathway).”); *and* Intergovernmental Panel on Climate Change (2023) AR6 Synthesis Report: Climate Change 2023, *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Arias P., Bustamante M., Elgizouli I., Flato G., Howden M., Méndez C., Pereira J., Pichs-Madruga R., Rose S. K., Saheb Y., Sánchez R., Ürge-Vorsatz D., Xiao C., & Yassaa N. (eds.), 36, 42 (“In terrestrial ecosystems, 3–14% of the tens of thousands of species assessed will likely face a very high risk of extinction at a GWL of 1.5°C. Coral reefs are projected to decline by a further 70–90% at 1.5°C of global warming (*high confidence*). At this GWL, many low-elevation and small glaciers around the world would lose most of their mass or disappear within decades to centuries (*high confidence*). Regions at disproportionately higher risk include Arctic ecosystems, dryland regions, small island development states and Least Developed Countries (*high confidence*). … The likelihood of abrupt and irreversible changes and their impacts increase with higher global warming levels (*high confidence*). As warming levels increase, so do the risks of species extinction or irreversible loss of biodiversity in ecosystems such as forests (*medium confidence*), coral reefs (*very high confidence*) and in Arctic regions (*high confidence*). Risks associated with large-scale singular events or tipping points, such as ice sheet instability or ecosystem loss from tropical forests, transition to high risk between 1.5°C–2.5°C (*medium confidence*) and to very high risk between 2.5°C–4°C (*low confidence*). The response of biogeochemical cycles to anthropogenic perturbations can be abrupt at regional scales and irreversible on decadal to century time scales (*high confidence*). The probability of crossing uncertain regional thresholds increases with further warming (*high confidence*).”).

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[454] Sun X., Wang P., Ferris T., Lin H., Dreyfus G., Gu B., Zaelke D., & Wang Y. (2022) *Fast Action on Short-lived Climate Pollutants and Nature-based Solutions to Help Countries Meet Carbon Neutrality Goals*, Adv. Clim. Chang. Res. 13: 564–577, 569 ("While more than 130 countries have committed to reaching net-zero emissions, only some of these jurisdictions include non-CO_2 pollutants in their pledges (Hale et al., 2021). As demonstrated by the summary of scientific studies above, countries need to include fast acting strategies on SLCPs and NbS in their climate policies to secure the most avoided warming on the way to meeting their carbon neutrality goals.").

[455] United Nations (9 August 2021) *Guterres: The IPCC Report is a code red for humanity*, UN Regional Information Centre for Western Europe ("UN Secretary-General António Guterres says a report published today by the Intergovernmental Panel on Climate Change (IPCC) is a "code red for humanity. … The alarm bells are deafening, and the evidence is irrefutable: greenhouse gas emissions from fossil fuel burning and deforestation are choking our planet and putting billions of people at immediate risk," the Secretary-General says in a statement.").

[456] Intergovernmental Panel on Climate Change (2018) *Summary for Policymakers*, *in* Global Warming of 1.5 °C, *Special Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 4 ("Human activities are estimated to have caused approximately 1.0 ºC of global warming above pre-industrial levels, with a *likely* range of 0.8 ºC to 1.2 ºC. Global warming is *likely* to reach 1.5 ºC between 2030 and 2052 if it continues to increase at the current rate. (*high confidence*)."). In addition to cutting CO_2 emissions and emissions of the super climate pollutants, the IPCC 1.5 ºC Report also calculates the need for significant CO_2 removal. *Id.*, at 17 ("C.3. All pathways that limit global warming to 1.5°C with limited or no overshoot project the use of carbon dioxide removal (CDR) on the order of 100–1000 $GtCO_2$ over the 21st century.").

[457] Xu Y. & Ramanathan V. (2017) *Well below 2 °C: Mitigation strategies for avoiding dangerous to catastrophic climate changes*, Proc. Nat'l. Acad. Sci. 114(39): 10315–10323, 10319 ("Box 2. Risk Categorization of Climate Change to Society. … Warming of such magnitudes also has catastrophic human health effects. Many recent studies (**50**, **51**) have focused on the direct influence of extreme events such as heat waves on public health by evaluating exposure to heat stress and hyperthermia. It has been estimated that the likelihood of extreme events (defined as 3-sigma events), including heat waves, has increased 10-fold in the recent decades(**52**). Human beings are extremely sensitive to heat stress. For example, the 2013 European heat wave led to about 70,000 premature mortalities (**53**). The major finding of a recent study (**51**) is that, currently, about 13.6% of land area with a population of 30.6% is exposed to deadly heat. … According to this study, a 2 °C warming would double the land area subject to deadly heat and expose 48% of the population. A 4 °C warming by 2100 would subject 47% of the land area and almost 74% of the world population to deadly heat, which could pose existential risks to humans and mammals alike unless massive adaptation measures are implemented, such as providing air conditioning to the entire population or a massive relocation of most of the population to safer climates. … This bottom 3 billion population comprises mostly subsistent farmers, whose livelihood will be severely impacted, if not destroyed, with a one- to five-year megadrought, heat waves, or heavy floods; for those among the bottom 3 billion of the world's population who are living in coastal areas, a 1- to 2-m rise in sea level (likely with a warming in excess of 3°C) poses existential threat if they do not relocate or migrate. It has been estimated that several hundred million people would be subject to famine with warming in excess of 4 °C (**54**). However, there has essentially been no discussion on warming beyond 5 °C. Climate change-induced species extinction is one major concern with warming of such large magnitudes (>5°C). The current rate of loss of species is ∼1,000-fold the historical rate, due largely to habitat destruction. At this rate, about 25% of species are in danger of extinction in the coming decades (**56**). Global warming of 6°C or more (accompanied by increase in ocean acidity due to increased CO_2) can act as a major force multiplier and expose as much as 90% of species to the dangers of extinction (**57**). The bodily harms combined with climate change-forced species destruction, biodiversity loss, and threats to water and food security, as summarized recently (**58**), motivated us to categorize warming beyond 5°C as unknown??, implying the possibility of existential threats.").

[458] 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

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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.").

[459] United Nations Environment Programme (2023) *One Atmosphere: An Independent Expert Review on Solar Radiation Modification Research and Deployment*, 1–38, 22 ("In the interests of academic freedom, it is suggested that no formal governance framework for SRM indoor research is required at this time. However, it would be advantageous to develop a set of norms or voluntary code of conduct that would promote reporting, transparency, inclusiveness and data-sharing. To govern small-scale outdoor SRM experiments or operational deployment of SRM systems, several existing frameworks could be relevant (Annex 5)… There is general agreement among this group of experts that governance of large-scale SAI deployment is valuable given the inherent risks associated with changing stratospheric conditions caused by large-scale interventions over long time periods (i.e. multiple decades). A broader framework for the governance of the stratosphere would address the changes that occur in the stratosphere from SAI experiments or deployment, and by other activities such as rocket launches, but might not address other concerns that are specific to SRM.").

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