Primer on Polar Warming and Implications for Global Climate Change

How fast action can slow the rate of global warming and protect the Arctic and Antarctic from devastating climate change impacts

Institute for Governance & Sustainable Development

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

Beginning in 2005, IGSD embarked on a "fast-action" climate mitigation campaign that will result in significant reductions of greenhouse gas emissions and will limit temperature increase and other climate impacts in the near term. The focus is primarily on strategies to reduce non-CO_2 climate pollutants as a complement to cuts in CO_2, which is responsible for more than half of all warming. It is essential to reduce both non-CO_2 pollutants and CO_2. Neither alone is sufficient to limit the increase in global temperature to a safe level. A three-level strategy of achieving carbon neutrality, slowing the rate of warming with the reduction of non-CO_2 climate pollutants, and removing carbon from the atmosphere are key to climate stability.

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This *Primer* is available on IGSD's website (http://www.igsd.org/primers/polar/) with active links to the references and periodic updates. IGSD's *Primer on HFCs* and *Primer on Short-Lived Climate Pollutants* are also available on IGSD's website. Unless otherwise indicated, all content in the *Primer* carries a Creative Commons license, which permits non-commercial re-use of the content with proper attribution. Copyright © 2019 Institute for Governance & Sustainable Development.

Preamble

This *Primer* covers the present and future impacts of climate change on the Polar Regions and what solutions and resources are available to slow the progression of climate change. The *Primer* discusses observations of recent warming as well as tipping elements and impending tipping points particular to the Polar Regions before a thorough discussion of the present observations and future projections for Arctic sea ice, permafrost, and the ice sheets of Greenland and Antarctica. The *Primer* also relates potential solutions to combat climate change, especially in the crucial near-term given the proximity to some tipping points. Furthermore, the *Primer* includes discussion of existing laws and policies as well as organizations and collectives working to protect the vulnerable Polar Regions.

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INTRODUCTION

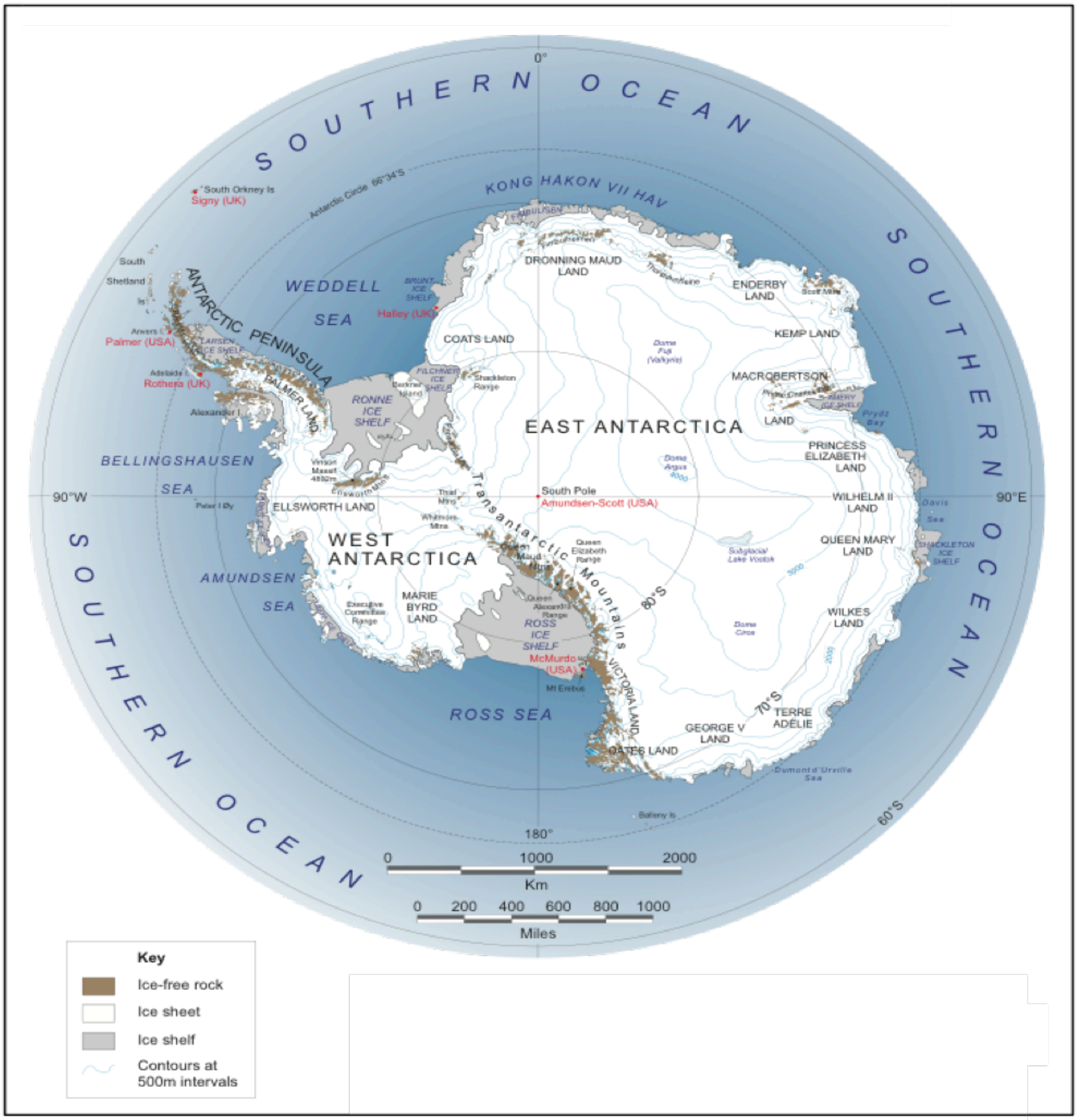
This Primer will focus on the impact climate change is already having on the Polar Regions, the projections for what will happen in the future, and what can be done about it. The Arctic is warming at twice the global rate,[1] but both poles are considered in this *Primer* because they are subject to a number of globally consequential climate tipping elements[2]—for which passing a critical threshold (tipping point) unleashes significant and often unstoppable change—and self-reinforcing climate feedbacks, the triggering of which can permanently alter the state of the global and regional climate through a domino-like effect.[3] Self-reinforcing feedbacks and tipping elements of the Polar Regions include: declining Arctic sea ice; thawing permafrost; and melting ice sheets in Greenland and Antarctica.[4] Another feedback—the poleward migration of mid-latitude clouds—plays a role in Arctic amplification, exacerbating warming and bringing the region closer to tipping points.[5]

Fig. 1: Arctic Region

This map of the Arctic was created by State Department geographers as part of the U.S. Chairmanship of the Arctic Council. (U.S. Department of State, Map of the Arctic Region (*last accessed* 23 May 2018).)

The Antarctic region is comprised of Antarctica and the Southern Ocean that surrounds the continent. Antarctica is divided into two parts: West Antarctica and the much larger East Antarctica. West Antarctica is home to the Antarctic Peninsula and also many ice shelves. *See* Figure 2.

Fig. 2: Antarctic Region



This map shows the major geographical features on the Antarctic continent and the USA and UK research stations, to accompany the Landsat Image Mosaic of Antarctica (LIMA). For information about LIMA and to access the imagery, go to http://lima.usgs.gov. (U.S. Geological Survey, [Antarctic Overview Map]() (*last accessed* 23 May 2018).)

Because the poles are routinely covered in snow and ice, they are part of the global cryosphere and are crucial to the climate system.[6] These frozen areas of the planet are particularly vulnerable to the rising temperatures that induce melting. The Arctic Ocean is covered in sea ice, and the Arctic region also includes the Greenland ice sheet and large areas of permafrost.[7] At the other pole, Antarctica is a massive, snow- and ice-covered continent that has ice-shelves floating over the ocean and sea ice surrounding the continent.[8]

Following the discussion of the current science, the *Primer* will detail priorities for policymakers and other interested parties for addressing climate change, especially as it pertains to the Arctic in the near-term and will impact the Antarctic region as warming continues. The Polar Regions are particularly susceptible to self-reinforcing feedbacks and recent warming suggests we may be perilously close to crossing tipping points that could trigger the various tipping elements, shifting the poles—and the planet—into a new climate state.[9] The priorities include what must be done to attain near-term success to slow the rate of warming as well as stabilize long-term climate.

Fast mitigation to cut the short-lived climate pollutants (SLCPs)[10]—super pollutants HFCs, methane, tropospheric ozone, and black carbon—can cut Arctic warming quickly, slow feedbacks, and reduce the risk of passing tipping points.[11] Fast mitigation also can slow the melting of the Greenland Ice Sheet and the Antarctic ice sheets, and thus slow the rate of sea level rise. Solutions exist to make fast cuts to SLCPs and to take other fast mitigation actions, and in many cases these solutions can be implemented through existing laws and institutions.

The mitigation measures discussed in detail in this *Primer* focus on slowing the near-term warming that will slow the progression of self-reinforcing feedbacks and avoid tipping points. Solutions include mitigation measures for SLCPs, especially those of methane and black carbon,[12] and HFCs being phased down under the 2016 Kigali Amendment to the Montreal Protocol.[13] Additionally, other existing legal and political frameworks showcase the current status of SLCP mitigation as well as opportunities for enhancing action for added benefit and greater likelihood of achieving the Paris Agreement goals.

RECENT WARMING, PROXIMITY TO 1.5 ºC, AND ARCTIC AMPLIFICATION

Global temperatures have increased 1.0 ºC above preindustrial levels.[14] The *IPCC Special Report on 1.5 ºC Warming* calculates that warming could reach 1.5 ºC above pre-industrial temperatures between 2030 and 2052 if warming continues at the current rate.[15] As global temperatures rise, the Arctic warms at twice the rate, making the region particularly vulnerable to climate change.

Climate change is accelerating from rising emissions, declining air pollution, and natural climate variability.[16] The rate of warming is accelerating and is projected to accelerate further in the coming years.[17] With a faster rate of change, human and natural systems are less able to adapt.[18] Already, almost a third of the world's population lives in a climate where deadly temperatures occur at least 20 days a year.[19] Climate change may cause disruptions to ecosystems with some species shifting their range—usually to higher latitudes—and others facing extinction.[20] In the Arctic, redistribution of species has brought new species into the region, but native species are struggling, which challenges traditional knowledge systems and food security.[21]

Recent warming observations

As a consequence of climate change and Arctic amplification (discussed below),[22] the Arctic has warmed 2 ºC, twice as much as the planet as a whole.[23] The rate of temperature increase also is accelerating. Since 1981, the rate of global annual temperature increase has more than doubled in recent decades to a rate of 0.17 ºC per decade, compared to 0.07 ºC per decade from 1880.[24] Every year since 1977 has had surface temperatures above the 20th century average, and record setting temperatures were set every thirteen years from 1880 to 1980, but since then, record temperatures are set roughly every three years.[25]

Globally, the year 2016 was the warmest on record, and 2018 was the fourth warmest year on record behind 2015, 2016, and 2017.[26] The trio of years of 2015–2017 all hit 1.0 ºC or higher above the 1880–1900 average, but 2018 was close, reaching 0.97 ºC above preindustrial temperatures.[27] The record heat of 2016 was partially fuelled by strong El Niño conditions in the first third of the year,[28] and 2017 was the warmest year without the added influence of El Niño.[29]

Table 1: Global average warming in 2018 and 2016 (warmest year on record)[30]

Organization	Warming in 2018	Baseline for comparison	Rank for 2018	Warming in 2016
NASA GISS[31]	0.83 ºC (1.5 ºF)	1951–1980	4th	0.99 ºC (1.78 ºF)
NOAA[32]	0.97 ºC (1.75 ºF)	1880–1900 (pre-industrial)	4th	0.94 ºC (1.69 ºF)
WMO[33]	1.0 ºC (1.8 ºF)	1850–1900 (pre-industrial)	4th	1.2 ºC (2.16 ºF)
Hansen *et al.* 2019[34]	1.1 ºC (2.0 ºF)	1880–1920 (pre-industrial)	4th	1.26 ºC (2.3 ºF)

Proximity to 1.5 ºC and timing of reaching 1.5 ºC and 2 ºC

As mentioned above, the IPCC stated that 1.5 ºC could be reached between 2030 and 2052, though natural climate variability could cause temperatures to cross the 1.5 ºC threshold for the first time even sooner, sometime between 2026 and 2031.[35] Emissions of the past, present, and future lock-in warming that will be realized years later.[36] If emissions continue at the current rate, the carbon budget to stay under 1.5 ºC will be exhausted in few years.[37] However, recent considerations of greenhouse gas emissions prior to 1850 suggest that the carbon budget may be even smaller and exhausted even quicker.[38]

Overall, CO_2 concentration has accelerated in recent years.[39] In the 1980s and 1990s, CO_2 increased by about 1.5 ppm/year, but from 2008 to 2017, the rate increased to around 2.2 ppm/year,[40] rising to approximately 2.63 ppm/year in 2018.[41] The extraordinarily long lifetime of CO_2—centuries to millennia[42]—means that the concentration of CO_2 in the atmosphere continues to increase even when emissions flatline. CO_2 emissions remained constant from 2014–2016,[43] but 2017 saw CO_2 emissions increase by 1.4%[44] and 2018 is projected to have a rise of 2.7% (with a possible range of 1.8 to 3.7 %).[45] This growth was the result of increased economic growth combined with cheaper fossil fuels and weaker policies relating to energy efficiency.[46] When compared to geologic history, anthropogenic emissions far outpace any other time period in the last 66 million year.[47]

Arctic amplification

The Arctic has warmed twice the global average, primarily driven by the "cascade of feedbacks that collectively amplify Arctic warming."[48] Arctic amplification describes the reality that the Arctic responds to global temperature changes more dramatically than lower latitudes.[49] The mechanisms driving the amplification include: reduced albedo from loss of sea ice and decreased snow cover (known as the ice-albedo feedback); increased water vapour in the Arctic atmosphere; altered cloud cover; added heat in the newly ice-free ocean areas; lowered rate of heat loss due to lower surface temperatures in the Arctic; and reduced air pollution.[50]

Temperatures in the Arctic from 2011 to 2015 were warmer than any year on record since the instrumental record began in 1900.[51] Under medium to high greenhouse gas (GHG) concentration scenarios, the Arctic is projected to warm to an annual average temperature of 4 to 5 ºC above late 20th century values before mid-century, which is twice what is projected for the Northern Hemisphere.[52]

Arctic amplification can alter large-scale atmospheric flow and contribute to extreme weather events beyond the Arctic.[53] Changes in the Arctic can influence weather systems passing through the mid-latitudes, including increasing the incidence of cold spells over land.[54] Arctic amplification also supports atmospheric conditions that promote enhanced Greenland melting,[55] and recent observations from Greenland corroborate the theory.[56]

Increased global temperatures will affect the Arctic through changes to clouds. Presently, clouds have a net negative forcing of –20 W/m^2, comprised of +30 W/m^2 from the greenhouse effect of clouds (absorbing and emitting longwave radiation from the surface back towards the surface) and –50 W/m^2 from the reflective cooling (reflecting incoming solar radiation).[57] Because of the large magnitude of the cloud radiative effect, small changes can result in large feedbacks.[58] (Feedbacks are covered in the next section.)

Global climate models suggest that changes in large-scale atmospheric circulation promote subtropical drying that causes a poleward shift in clouds. Observations in storm track cloudiness from 1983–2003 corroborate these model simulations, adding that reduced planetary albedo from clouds shifting to areas with less sunlight will reduce the cloud-albedo effect and amplify warming.[59] Observations show that together, the poleward shifting of the clouds and the higher tops contribute to warming the surface, enhancing warming and setting the stage for further changes in cloud patterns and cloud heights in the future.[60]

Unmasked warming with reduction of aerosols

Due to common sources, reducing emissions of CO_2 and other greenhouse gases also removes aerosols from the atmosphere, which is beneficial to human health. However, if emissions suddenly ceased, the earth would continue to warm. Ramanathan and Feng (2008) caclculated—and Ramanathan and Xu (2010) confirmed—that committed warming may be as high as 2.4 ºC and that aerosols are the reason why we have yet to see all of the warming from the greenhouse gases that have so far been released into the atmosphere.[61] Many aerosols (particularly sulphates) have a cooling effect, exerting 1.8 W/m^2 of negative radiative forcing on the climate,[62] which counters the positive radiative forcing from greenhouse gases.[63]

Not all aerosols have a negative radiative impact on the climate. Black carbon—and brown carbon co-emitted alongside it—are notable exceptions. Like other aerosols, black carbon only remains in the atmosphere for a very short time, a few days to weeks.[64] Black carbon has a global warming potential of 900 (120–1,800) times greater than CO_2[65] and directly warms the atmosphere by absorbing incoming solar radiation and emitting it as heat and indirectly warms the atmosphere through cloud formation.[66]

Black carbon is co-emitted with other pollutants and comes from a myriad of sources, including diesel engines and industrial and residential coal use.[67] Some organic carbon that is co-emitted with black carbon also absorbs some solar radiation and is known as "brown carbon".[68] The warming effect of brown carbon offsets the cooling effect of light organic carbon, leaving the warming effect from black carbon untouched and creating an overall warming from organic carbon emissions.[69]

Reducing aerosols from air pollution is critical to protecting human health and provides a co-benefit to reducing overall emissions, but policymakers must be aware that in reducing these pollutants that cool the atmosphere will require enhanced measures against those pollutants that warm the atmosphere to account for the unmasking of the warming as pollution policies take effect.[70]

SELF-REINFORCING FEEDBACKS AND TIPPING ELEMENTS

The Polar Regions are already exhibiting signs of rapid warming, more so than the global average. At the same time, the Polar Regions are home to some of the most significant self-reinforcing feedbacks and tipping points.[71] These "wild cards" of the climate system create relatively abrupt shifts to the climate regime, some of which are irreversible on a human time scale. The amplified warming from self-reinforcing feedbacks brings tipping elements closer to the point of no return. Slowing global warming—and the warming in the Polar Regions—is essential to avoiding triggering the cluster of tipping elements whose tipping points exist between the 1.0 ºC of warming already experienced[72] and the 1.5 and 2 ºC of warming goals.[73] *See* Figure 3.

Fig. 3: Tipping elements and temperature ranges of their tipping points

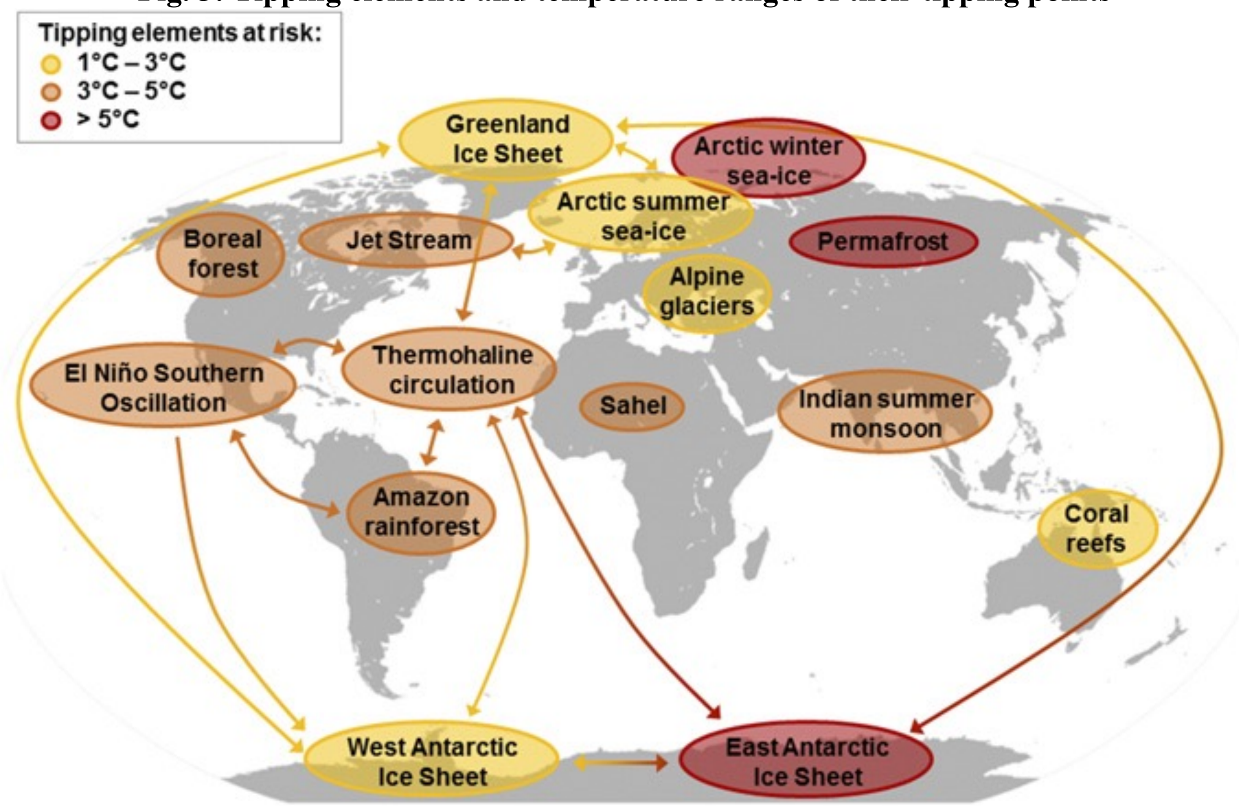


Fig. 3. Global map of potential tipping cascades. The individual tipping elements are color-coded according to estimated thresholds in global average surface temperature (tipping points) (12, 34). Arrows show the potential interactions among the tipping elements based on expert elicitation that could generate cascades. Note that, although the risk for tipping (loss of) the East Antarctic Ice Sheet is proposed at >5 °C, some marine-based sectors in East Antarctica may be vulnerable at lower temperatures (35–38). (Steffen W., *et al.* (2018) *Trajectories of the Earth System in the Anthropocene*, PROC. NAT'L. ACAD. SCI. 115(33):8252–8259, 8255.)

Understanding self-reinforcing feedbacks and critical thresholds of tipping elements

Warming has the potential to unleash self-reinforcing feedbacks, where some aspect of the climate system changes in such a way that amplifies warming.[74] For example, declining Arctic sea ice leads to less global reflectivity, which allows more solar energy to be absorbed at the surface that then leads to additional warming.[75] Recent observations of the Arctic's warming temperatures, declining sea ice, melting glaciers, and thawing permafrost suggest that the Arctic is already evolving into a new climate state.[76] At the other end of the globe, Antarctica may be inching closer to abrupt climate change, where destabilisation of the West Antarctic Ice Sheet threatens a rapid collapse into the ocean that will raise sea levels extensively.[77]

In accelerating warming, subsystems of the Earth's climate—so called "tipping elements"[78]—have the potential to be shifted into new regimes.[79] Once these tipping elements surpass a critical threshold—the "tipping point"—the subsystem is slated to be different in the future and thus ceases to exist as presently understood.[80] A tipping point is the critical threshold of a tipping element where a small change can trigger a much larger (and nonlinear) response that alters the state of the system and leads to a new climate regime.[81] Tipping points for multiple tipping elements could be reached during this century,[82] and many of these tipping elements may already be in motion and accelerating change.[83]

Fig. 4: Breakdown of tipping points within temperature ranges

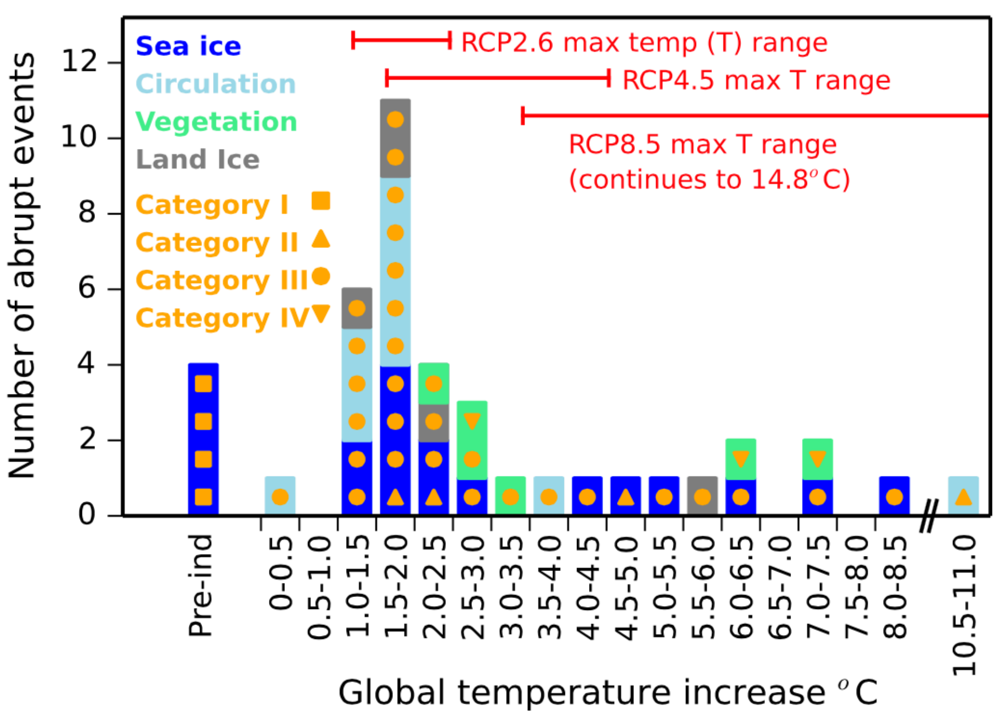


Fig. 4. Abrupt shifts as a function of global temperature increase. Shown are the number of abrupt climate changes occurring in the CMIP5 database for different intervals of warming relative to the preindustrial climate. (Drijfhout S., *et al.* (2015) *Catalogue of abrupt shifts in Intergovernmental Panel on Climate Change climate models*, PROC. NAT'L. ACAD. SCI. 112(43):E5777–E5786, E5784.)

Of thirty-seven tipping elements identified from IPCC models, eighteen are likely to occur with 2 ºC of warming or less, with six likely between 1.0 ºC and 1.5 ºC and eleven between 1.5 ºC and 2 ºC.[84] *See* Figure 4.

Timing and tipping points

Tipping points are difficult to predict because of the uncertainties associated with regional warming as well as the influence of internal climate variability.[85] Some tipping points, such as sea-level rising 6–9 metres from melting ice sheets, may take millennia to be fully realized and thus give humanity and ecosystems more time to adapt.[86] Other tipping points may happen on much shorter timescales, with little to no warning, providing humanity and ecosystems with little to no time to adapt.[87] At the same time, ice sheet dynamics and non-linear changes to ice sheets can lead to irreversible loss that can be difficult to model and predict.[88] Understanding feedbacks requires understanding of the range of possibility with uncertainty, especially with modelling key feedbacks like the loss of Arctic sea ice,[89] and while some of the changes from feedbacks and tipping points are uncertain, they come with the potential for high-impact.[90]

While some tipping points may have already been passed, fast mitigation can still prevent passing other tipping points and the compounding effect of cascading tipping points.[91] Surpassing some tipping elements may trigger other tipping elements to breach their critical thresholds, exacerbating impacts and costs of climate change.[92] Feedbacks and the climate-economic shocks emanating from them may become the most important contributors to the cost of climate change.[93]

ARCTIC SEA ICE

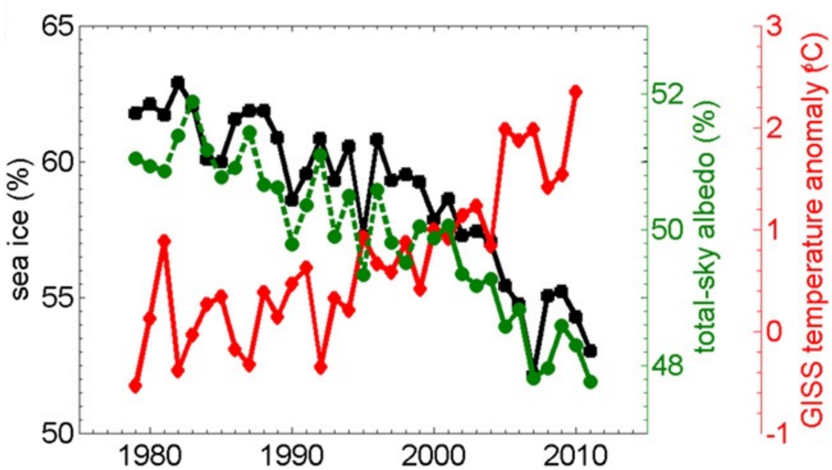
Arctic sea ice is sensitive to increasing temperatures, and as the Arctic was warmed more than the global average, the Arctic sea ice has been impacted.[94] From 1979 to 2011, the Arctic lost nearly 40% of its sea ice.[95] Since then, Arctic sea ice has repeatedly set record lows and consistently been below the long-term average.[96] Ice thickness has also decreased, which has led to less older ice that is more stable as younger ice is more susceptible from breakup.[97] With less ice in the Arctic, more solar radiation is absorbed in the region, which leads to more warming that then leads to less ice in a powerful feedback loop.[98] The Arctic could become ice free during the summer months within a decade.[99] Limiting warming to 1.5 ºC leads to far fewer summers of an ice-free Arctic than if warming is limited to 2 ºC.[100]

Reduced Arctic sea ice and self-reinforcing warming

The Arctic has already warmed by nearly twice the global average.[101] There is little lag time between rising temperatures and decreasing sea ice area.[102] Temperatures seen in the Arctic during November and December 2016 would be "extremely unlikely…in the absence of human-induced climate change,"[103] and these warmer temperatures contributed to the reduced sea ice extent in 2016.[104] A 2018 study found that 60% of the exceptional Arctic warmth in 2016 was likely attributable to anthropogenic climate change.[105]

As the Arctic warms, sea ice melts and exposes the darker water beneath, which absorbs more incoming solar radiation and further warms the region.[106] Moreover, the persistently warmer water hinders significant ice growth in winter.[107] Less ice makes for a less reflective surface (decreased albedo) that results in localized warming, which is exacerbated as the Arctic continues to lose ice in a positive feedback loop.[108]

Fig. 5: Change in temperature (red), sea ice (black), & albedo (green)



All-sky albedo [green line]…compared with annual-mean observed sea ice area (as a fraction of the ocean in the Arctic region) [black line] and surface air temperature averaged over the ocean in the Arctic region [red line]. (Pistone K., *et al.* (2014) *Observational Determination of Albedo Decrease Caused by Vanishing Arctic Sea Ice*, PROC. NAT'L. ACAD. SCI. 111(9):3322–3326, 3325.)

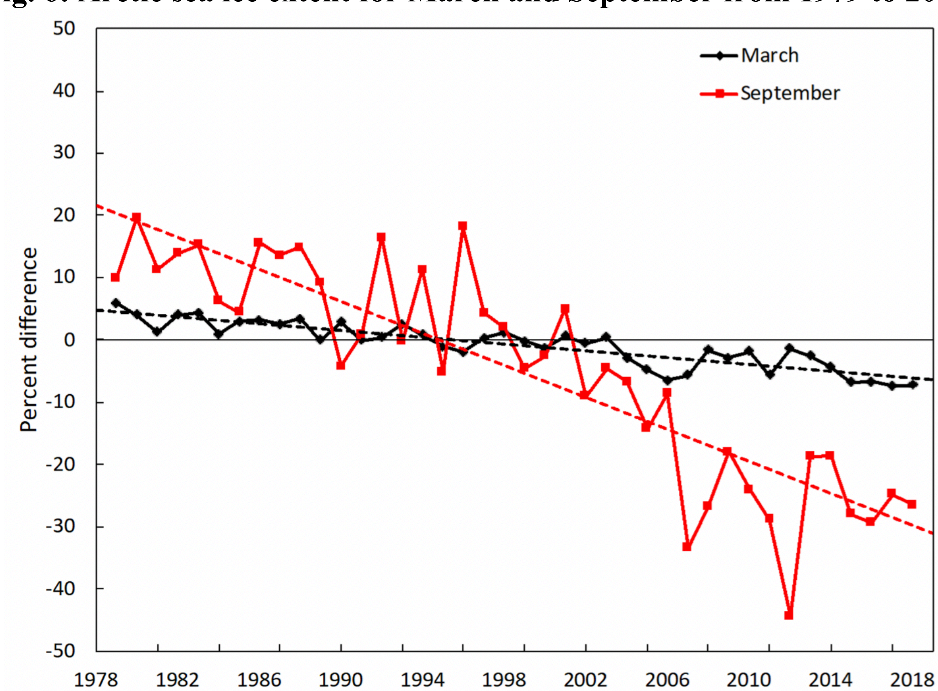
From 1979 to 2011, the summer minimum extent of Arctic sea ice decreased by 40%, greatly reducing the reflectivity of the planetary surface and altering the amount of solar energy absorbed into the region instead of being reflected back out to space.[109] This caused an increase of climate forcing in the Arctic region of 6.4 ± 0.9 W/m^2.[110] If this change in radiative forcing of the Arctic were averaged globally, the forcing exerted by the loss of sea ice would be 0.21 ± 0.03 W/m^2, which is equivalent to 25% of the forcing globally from CO_2 during the same period.[111]

Another feedback mechanism that accelerates the reduction of Arctic sea ice is the vertical feedback mechanism, whereby the reduction of sea ice exposes ocean water that releases heat into the lower atmosphere, warming the lower atmosphere and thus melting the sea ice.[112] Unlike the ice-albedo feedback that only operates when the region is exposed to solar radiation during the summer months, the vertical feedback mechanism continues in the winter.[113]

Recent observations and climatology of the extent of Arctic sea ice

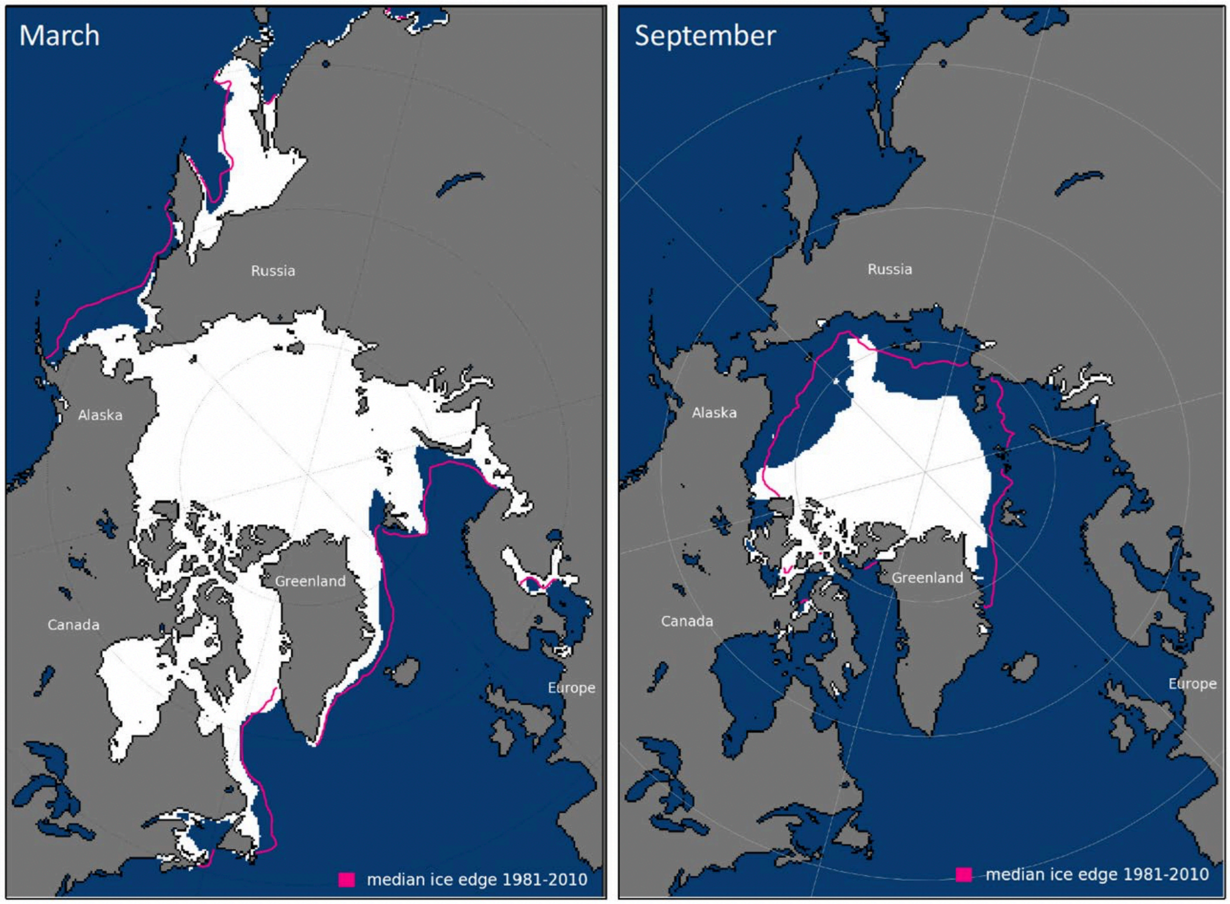
The Arctic typically achieves its winter maximum sea ice in March and its summer minimum in September. On 13 March 2019, Arctic sea ice covered 14.78 million square kilometres, which is 860,000 square kilometres below the 1981–2010 average, making the 2019 maximum the seventh lowest on record.[114] The years 2015 to 2018 hold the records for lowest maximum sea ice extent, and 2017 was the lowest on record.[115]

Fig. 6: Arctic sea ice extent for March and September from 1979 to 2018



Time series of ice extent anomalies in March (the month of maximum ice extent) and September (the month of minimum ice extent). The anomaly value for each year is the difference (in %) in ice extent relative to the mean values for the period 1981-2010. The black and red lines are least squares linear regression lines. The slopes of these lines indicate ice losses of -2.7 ± 0.5% and 12.8 ± 2.3% per decade in March and September, respectively. Both trends are significant at the 99% confidence level. (Perovich D., *et al.* (2018) *Sea Ice*, *in* ARCTIC REPORT CARD 2018, 27.)

Fig. 7: Arctic sea ice extent for March 2018 and September 2018



Average monthly sea ice extent in March (left) and September (right) 2018 illustrate the respective winter maximum and summer minimum extents. The magenta line indicates the median ice extents in March and September, respectively, during the period 1981-2010. (Perovich D., *et al.* (2018) *Sea Ice*, *in* ARCTIC REPORT CARD 2018, 26.)

Arctic sea ice achieved its 2018 summer minimum extent of 4.59 million square kilometres on September 19 and 23, which is tied for sixth lowest minimum extent in the satellite record and 163 million square kilometres below the 1981–2010 median minimum ice extent.[116] While the minimum sea ice extent did not set a record as the lowest sea ice extent, the last twelve years mark the twelve lowest minimum sea ice extent measures in the satellite era.[117]

The past five years have been the warmest in the Arctic, with 2018 being the second warmest and 2016 the overall warmest.[118] The average surface temperature, as measured at land stations north of 60 ºN, from October 2015 to September 2016 was 2.0 ºC above the 1981–2010 average, which is about 3.5 ºC warmer than the start of the 20th century and the warmest for the region since 1900 (when the instrumental records began).[119] In November 2016, Arctic temperatures reached astounding levels above average, up to 15 ºC above normal temperatures.[120] The monthly average sea ice extent for November has declined 5% per decade between 1978 and

2016.[121] In December 2016, Arctic sea ice covered about 80% of the area around the North Pole; it usually covers closer to 95%.[122]

Fig. 8: Monthly anomalies of Arctic sea ice extent from November 1978 to July 2018

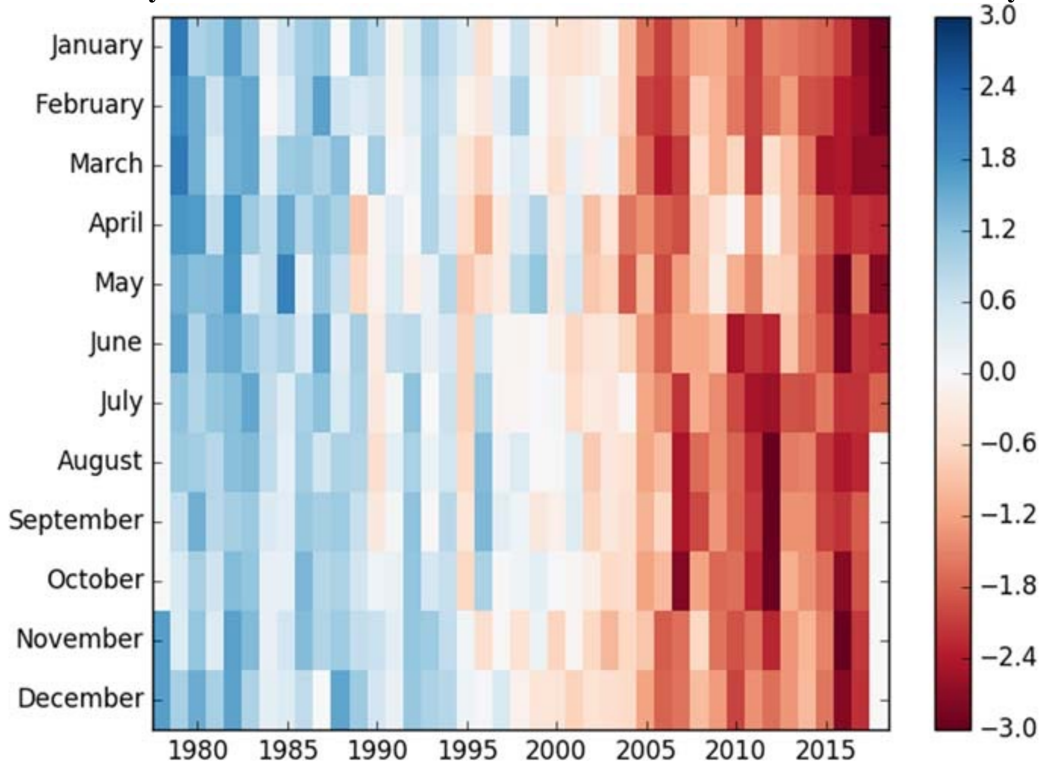


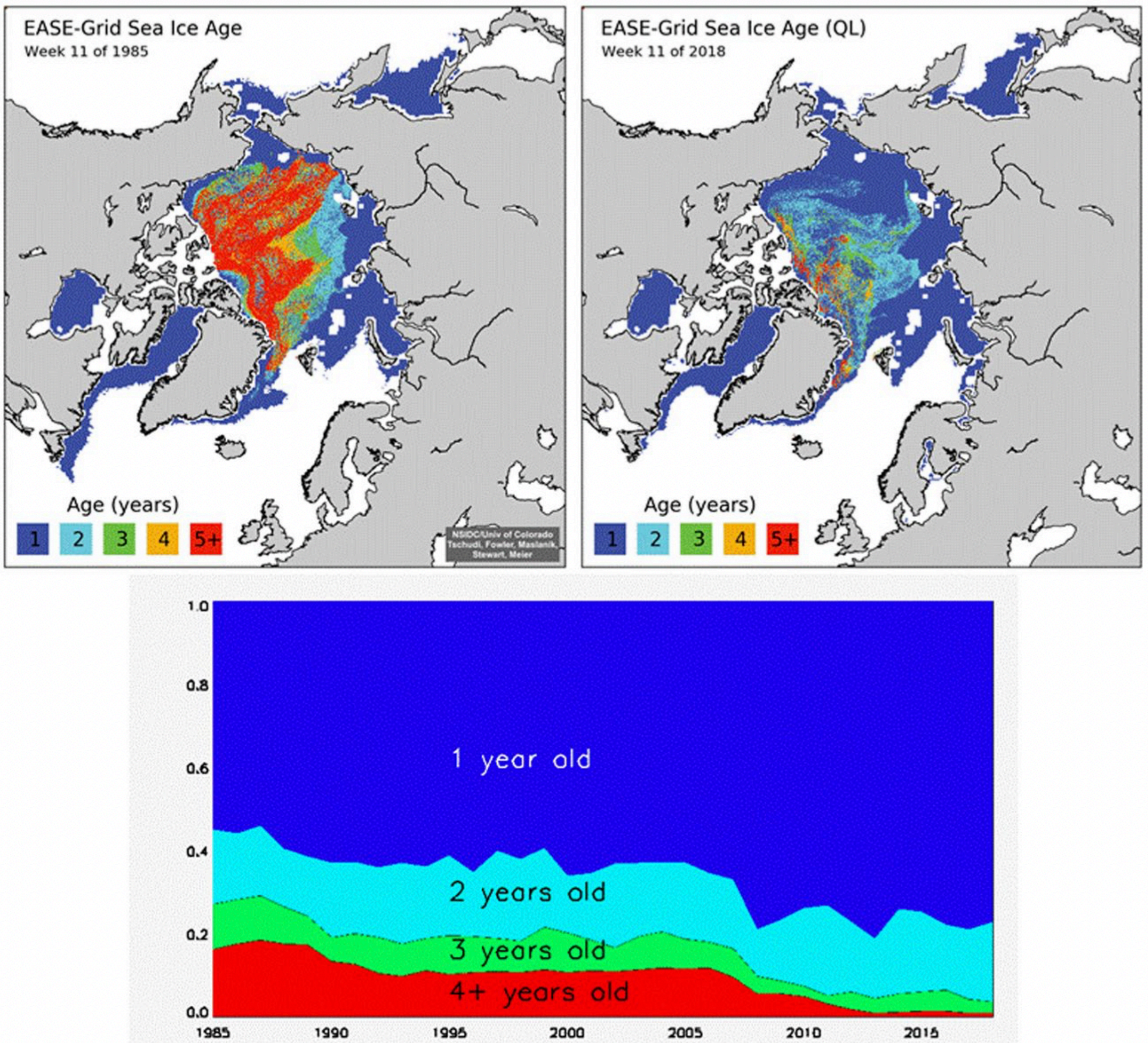
Figure 1. Anomalies in monthly sea-ice extent from November 1978 through July 2018. The colors indicate how many standard deviations sea-ice extent in a given month was above or below the mean sea-ice extent of the reference period 1981–2010. (Stroeve J. & Notz D. (2018) *Changing state of Arctic sea ice across all seasons*, ENVTL. RESEARCH LETTERS 13(103001):1–23, 6.)

Leading up to the winter maximum of 2018, temperatures during February 2018 were 10–12 ºC above average over the Chukchi and Bering Sea.[123] At the end of February 2018, temperatures near the North Pole were 20–30 ºC (36–54 ºF) above average, making this the third year in a row with extreme heat waves during the winter over the Arctic Ocean.[124] Dramatically warmer temperatures were also observed in northern Greenland with hourly temperature observations reaching above freezing (0 ºC) 59 times while previous years saw far fewer—if any—similar spikes in hourly temperature observations.[125] February 2018 also marked the first time that a shipping vessel was able to traverse the Arctic's northern sea route during winter without the assistance of an icebreaker.[126] As Arctic sea ice declines, the area will be opened up for additional shipping as well as for resource extraction, which can increase pollution in the region.[127]

Thickness of sea ice

Sea ice thickness and overall volume are equally important to the discussion of the Arctic and the effect added warming has on the region. Throughout the Arctic, the amount ice retained from year to year is decreasing, with four-year old ice showing a significant decline in recent years, which is paired with increasing first year ice that is more delicate.[128] The thickness of Arctic sea ice has declined by 65% from 1975–2012, which has led to less multi-year ice and more first year ice.[129] The shift to younger and thinner ice in the Arctic Ocean is indicative of a new climate regime.[130]

Fig. 9: Quantity and extent of old and young Arctic sea ice



Sea ice age coverage map for (a) March 1985 and b) March 2018. (c) Sea ice age coverage by year, 1985-2018. (Perovich D., *et al.* (2018) *Sea Ice*, *in* ARCTIC REPORT CARD 2018, 28.)

The age of sea ice is crucial to the stability of the Arctic as older ice is often thicker and more resilient to changes in atmospheric and oceanic warming than younger ice.[131] Even if ice rebuilds after a summer of significant loss, the newer ice is not nearly as thick and this lesser volume of ice is more at risk of melting in the subsequent summer.[132] The rebuilding of ice in the winter months is crucial to maintaining ice year round, and the progression to more first year ice increases the potential for ice-free Arctic.[133] In March 2016, first-year ice made up 78% of the ice cover, compared with 55% in 1985.[134] Very old ice (greater than 4 years old) made up only 0.9% of the ice pack in 2017 whereas in 1985, very old ice constituted 16% of the sea ice;[135] in 2018, only 1% of the Arctic sea ice was very old ice.[136]

Projections for the future and the likelihood of ice-free Arctic

Predictions for when the Arctic will become ice free[137] vary, but the loss of summer sea ice is likely to happen within the next few decades, potentially as early as the 2030s.[138] Scientists using "trends" to predict an ice-free Arctic suggest that the Arctic could be ice free within the next decade.[139] Others embrace the randomness of natural variability in the climate system alongside the observations to statistically determine an outcome, and they project that the Arctic could be ice free around 2030.[140] Modelling studies have revealed a large range of possibilities for when the Arctic will be ice free, with a median range around 2060 and some studies projecting as early as 2040.[141]

Keeping warming under 2 ºC greatly reduces the risk of an ice-free Arctic, and keeping warming under 1.5 ºC even more so.[142] Warming of 2 ºC globally leads to a 1-in-3 chance of an ice-free Arctic in September, while warming of 1.5 ºC has only a 1-in-40 chance.[143] The probabilities of having an ice-free Arctic before reaching 1.5 ºC, 2 ºC, or 3 ºC warming are 10%, 80%, and 100%, respectively.[144] Because ice-free conditions are related to temperature, an ice-free Arctic in a 1.5 ºC warmed world is more likely to be an isolated event, but a 2 ºC world is more likely to see repeated instances of an ice-free Arctic.[145] Limiting warming to 1.5 ºC requires emissions to be reduced by at least 5% per year globally and negative net carbon emissions to be achieved by the latter half of this century.[146]

The probability of an ice-free Arctic continues to increase even after temperatures have stabilized because of the internal variability of Arctic sea ice.[147] Internal variability in the Arctic can add about two decades of uncertainty to when the Arctic projected be ice free,[148] which extends the range of the first ice-free Arctic to sometime between 2032 and 2053 under a business-as-usual emissions scenario (RCP8.5[149]) or 2043 to 2058 for a moderate emissions scenario (RCP4.5).[150] The timing of the first ice-free Arctic (based on temperature thresholds) is also influenced by internal variability of the region, and in some of models, the Arctic becomes ice free with 1.4 ºC of warming and others with 1.9 ºC of warming.[151]

Even if the Arctic is not completely ice free with 1.5 ºC of warming, 55% of the September sea-ice extent measurements are projected to be below the 2012 record minimum; this increases substantially for 2 ºC of warming where 98% of September sea-ice extent measurements will likely exceed the record minimum.[152]

Concern should not be just for when the Arctic sea ice is completely gone because the reduced sea ice itself affects the climate through more absorption of heat that delays freeze up and other issues relating to heat exchange as well as localized impacts like increased permafrost temperatures and Greenland melt.[153] There has been an increase in rapid ice loss events—where more than 800,000 square kilometres of ice is lost in seven days—since 2005, with some of the most dramatic events happening in 2007, 2014, and 2015.[154] Rapid ice loss events in the Arctic lead to warming in the surrounding land areas, which can lead to permafrost degradation.[155] As observed during the passage of a particularly strong Arctic storm, the lack of sea ice alters the heat fluxes, leading to extreme warming in the Arctic.[156]

Cumulative emissions and aerosols contributing to Arctic warming and ice loss

Researchers have established a linear relationship between average September sea-ice extent and cumulative carbon dioxide emissions such that 3 ± 0.3 m^2 of September sea ice were lost for each metric ton of carbon dioxide emitted.[157] This would lead to September sea-ice area being completely lost with an additional 1000 Gt CO_2.[158]

While this relationship of emissions to lost sea ice may serve as an attractive tool to illustrate and communicate individual emissions to climate impact,[159] changes to the Arctic are affected by more than just CO_2 emissions.[160] Specifically, changes in anthropogenic aerosols affected incoming solar radiation such that reduction in air pollution led to declining aerosols that contributed to Arctic warming following years of cooling the Arctic during the mid-20th century.[161]

Decreased Arctic sea ice and more cyclones and larger ocean waves

Thinner sea ice is more predisposed to melting by changing wave conditions and increased cyclones.[162] Less sea ice in the Arctic Ocean allows ocean waves to grow larger, allowing for an acceleration of ice breakup and retreat.[163] Warming Arctic conditions also leads to a greater number of cyclones and more intense cyclones.[164] Intense cyclones within the Arctic increase the ice melt.[165] Winds and waves from the cyclone break up the ice as the winds move the ice more quickly and the waves induce ice fragmentation.[166] These storms stir warmer ocean water toward the bottom of the sea ice, enhancing the melt.[167]

As an example, a storm in August 2012 lasted a few days, yet had a lasting impact on the sea ice that remained for roughly a half month.[168] A similar storm occurred during 2007, which was the previous record holder for minimum September sea ice, but the 2012 storm created a larger disturbance to the sea ice because the ice was much thinner and susceptible to disintegration by the storm.[169] For this reason, when less ice is present in the Arctic, the remaining ice is more prone to damage from cyclones.

Teleconnections—what happens in the Arctic does not stay in the Arctic

Atmospheric teleconnections extend the impacts of the changing Arctic around the globe, highlighting the fact that changes in the Arctic are not just a problem for the Arctic but for the planet as a whole. Arctic amplification and declining sea ice have been linked to large-scale changes in atmospheric circulation throughout the Northern Hemisphere.

Because the Arctic has warmed faster than the global average, there is less of a temperature difference between the equator and the pole. This causes the winds that blow from west to east over the mid-latitudes to weaken.[170] As a result, storm systems in the mid-latitudes are slowed in their progression eastward, leading to more dramatic precipitation events.[171] Overall, these events have been happening more frequently in recent years.[172] While many atmospheric conditions may influence the jet stream that moves these systems, Arctic amplification is one of the likely culprits.[173]

Of the weather extremes predicted to occur in a warming world, extreme cold and more intense snowstorms have increased over the U.S. and Eurasia,[174] with the eastern third of the U.S. being most affected.[175] Even when compared with other climate features like the El Niño-Southern Oscillation (ENSO), changes in the Arctic have had the greatest influence on mid-latitude weather.[176]

Cvijanovic *et al.* (2017) made a connection of declining Arctic sea ice affecting the precipitation over California. This study found that loss of Arctic sea ice led to changes in the tropical convection that triggered a response in the North Pacific that contributed to steering precipitation away from California.[177] Given the anthropogenic impact on Arctic sea ice and the connection demonstrated here, this study lends further attribution of human-induced climate change on the droughts in California.[178] The evidence suggests that the decrease in Arctic sea ice increases the chance of California being drier. This is not the same as California being drier every year; for a 20-year average, the change in precipitation is 10–15% less than the long-term average.[179] Additionally, this evidence does not directly connect the recent California drought with the present loss in Arctic sea ice.[180] Furthermore, the Cvijanovic study was tailored to consider the teleconnections between Arctic sea ice and precipitation over California, and other atmospheric circulations and climate forcings foster uncertainty as to the extent of the direct connection.[181]

Reversibility with cooler temperatures or geoengineering

Unlike other tipping elements where regime changes take millennia to reverse, the rapid response of sea ice to temperatures suggests that sea-ice recovery is theoretically possible if CO_2 concentrations—and eventually temperatures—return to more manageable levels.[182] However, research shows that even under the most stringent of emissions scenarios outlined by the IPCC (RCP2.6), sea ice is not likely to rebound within this century.[183] Even though full recovery of Arctic sea ice will take centuries, the modelled response time demonstrates that sea ice begins to recover when temperatures begin to decrease.[184]

One proposed project for Arctic sea ice recovery is a geoengineering project that would use wind-powers pumps to pump ocean water onto the surface of the sea ice to increase its thickness over time.[185] Deploying the project over 10% of the Arctic would cost $50 billion per year for ten years and require steel equivalent to 13% of U.S. steel production and 5% of the world's container shipping capacity.[186] Another project, Ice911, has proposed preserving Arctic ice through application of eco-safe reflective sand that maintains the natural reflectivity of the ice.[187]

While Artic ice management can impact the ice-albedo feedback, like other geoengineering techniques, the process cannot address other climate change impacts concerns like overall CO_2 concentrations and ocean acidification,[188] and there are a myriad of other questions about the feasibility of the project, ability to maintain the machinery in the harsh Arctic conditions, and potential environmental impacts.[189]

Others have suggested regionally focused geoengineering through sulphate injection into the stratosphere above the Arctic to increase the albedo in the region and reduce warming.[190] However, success would demand extensive international cooperation, thousands of flights per day to get the aerosols into the atmosphere, and any disruption to the injections would see an immediate return of the warming.[191] Furthermore, sulphate injections can affect ozone layer recovery by reducing the amount of protective ozone in the stratosphere above Antarctica.[192]

PERMAFROST

Permafrost is soil that stays below freezing temperatures for at least two consecutive years.[193] Permafrost covers roughly 15 square million kilometres of the Earth's surface.[194] Increased temperatures can lead to irreversible thawing of permafrost that can amplify warming by releasing carbon dioxide and methane into the atmosphere.[195] Permafrost is incredibly sensitive to temperature, and 65–85% of emissions from permafrost can be avoided if anthropogenic emissions are far less than a business-as-usual scenario.[196] Because the process of building up carbon in permafrost operates on a millennial timescale, rapid release of permafrost carbon is irreversible on a human timescale.[197]

Defining the permafrost-carbon feedback

When permafrost thaws, organic matter is broken down into carbon dioxide (CO_2) and methane (CH_4) that is released into the atmosphere.[198] There are four mechanisms through which permafrost thaws and releases carbon into the atmosphere: thickening of the active layer, talik formation, thermokarst development, and river and coastal erosion.[199] The active layer is the upper layer of the soil that thaws and refreezing each year (*see* Figure 10).[200] Talik is an unfrozen layer of soil that has a high moisture content and temperature conducive to carbon release.[201] Thermokarst lakes form when ice-rich soil thaws and the ground collapse, forming depressions that when filled with water are even more favorable for carbon release and additional permafrost thaw.[202] Permafrost can release carbon as river discharge changes as well as along coastal boundaries from rising sea levels and wave and storm damage.[203]

Fig. 10: Schematic diagram of permafrost feedback mechanism of deepening active layer

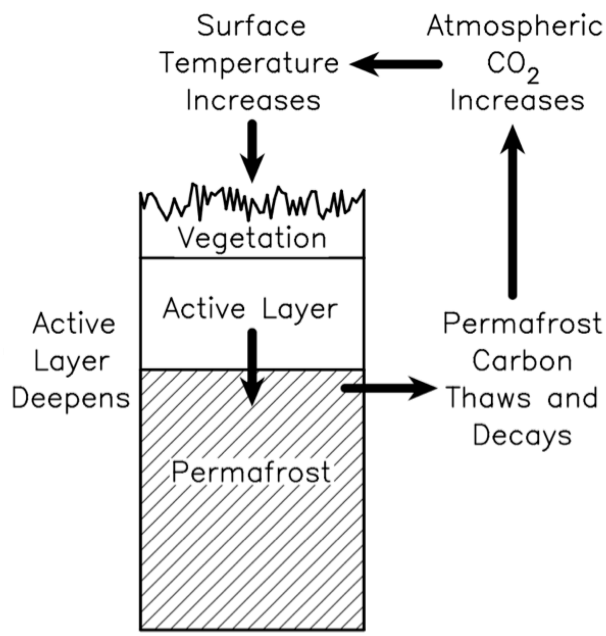


Fig. 1. A schematic showing the basic dynamics of the permafrost carbon feedback (PCF). (Schaefer K., *et al.* (2011) *Amount and timing of permafrost carbon release in response to climate warming*, TELLUS SERIES B CHEMICAL & PHYSICAL METEOROLOGY 63(2):165–180, 166.)

Determining the permafrost-carbon climate feedback requires an understanding of how much carbon could be released, how quickly that will happen, and whether the emissions of carbon are released as carbon dioxide or methane.[204] The impact that methane released from thawing permafrost will have on the global climate varies across studies, ranging from 25%[205] to 40% of the total warming.[206] Part of the discrepancy comes from the difference in soil types. Oxic soils are drained soils ("dry"), and anoxic soils are water-saturated soils ("wet"). With dry soils, the microorganisms oxidize organic carbon into carbon dioxide.[207] In wet soils, the decomposition rate is slowed due to the presence of the water, but the environment is conducive to the formation of both carbon dioxide and methane, which can have a greater impact on the climate because of methane's super pollutant characteristics.[208]

Some researchers have concluded that the permafrost-carbon feedback is strongest for dry soils.[209] But others noted that dry soils only release carbon dioxide, and then after once some time has passed, the wet soils release both carbon dioxide and methane that will, in the end, have a far greater impact on climate change.[210] Permafrost impedes drainage of the soils, so it is likely that the permafrost would create anoxic soil environments, which—given the release of both carbon and methane, the latter having a much higher global warming potential (GWP)—potentially leads to more warming.[211]

Current state of permafrost

Permafrost covers about 15 million square kilometres.[212] Areas with >90% coverage is continuous permafrost, 50–90% coverage is discontinuous permafrost, 10–50% coverage is sporadic permafrost, and less than 10% permafrost are isolated patches.[213]

The amount of greenhouse gases released from permafrost in the past 50 years has been relatively small, but about 50% of the world's soil carbon is contained within the Arctic.[214] Vast amounts of soil carbon could be released by 2050 as a result of warming temperatures, further accelerating warming.[215] With recent warming, Alaskan soils have already been shown to be a carbon source from 2012–2014, and for the October to December period, CO_2 emissions rates increased 73% since 1975.[216]

Because the high-latitude regions have the largest stocks of soil carbon and the fastest rates of warming, the "overwhelming majority of warming-induced soil [carbon] losses are likely to occur in Arctic and subarctic regions."[217] Assuming 2 ºC of warming under business-as-usual, by 2050 soils would release 55 ± 50 Gt of carbon (equal to 200 billion tonnes of CO_2), increasing CO_2 concentration by 25 ppm,[218] equivalent to 12–17 per cent of the expected emissions in 2050.[219]

Approximately 3.4 million square kilometres of permafrost have thawed in the twentieth century.[220] Globally, permafrost has warmed 0.29 ºC between 2007 and 2016, with some regions warming even more.[221] In the Northern Hemisphere, permafrost as deep as 20 metres has warmed 2–3 ºC in the past two decades.[222] Near-surface permafrost has warmed by more than 0.5 ºC in recent years, and the depth of the summer thaw has increased.[223]

Fig. 11: Soil carbon content in the Arctic Region

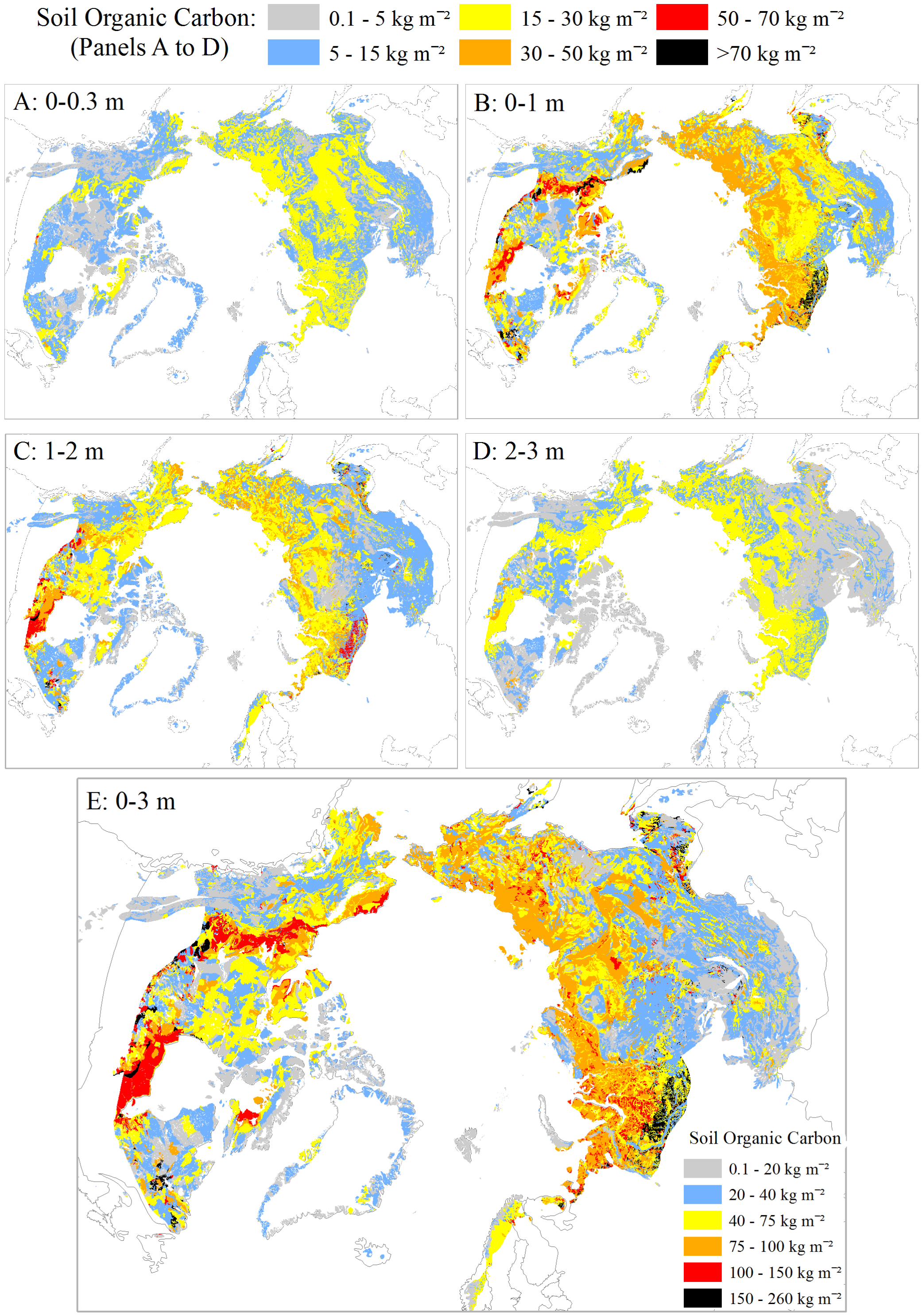


Figure 3. Map of estimated 0–3 m SOC storage (kg C m^{-2}) in the northern circumpolar permafrost region. Panels show 0–0.3 m and 0–1 m SOC calculated subdivided following NCSCD regions while 1–2 m and 2–3 m SOC is calculated subdivided for areas of thick thin sedimentary overburden. Projection: Azimuthal Equidistant, datum: WGS84. (Hugelius G., *et al.* (2014) *[Estimated stocks of circumpolar permafrost carbon with quantified uncertainty ranges and identified data gaps](#)*, BIOGEOSCIENCES 11:6573–6593, 6581.)

Permafrost in Alaska has set record high temperatures, increasing between 0.21 ºC and 0.66 ºC since 2000.[224] Active layer thickness—the depth of permafrost that thaws in summer and refreezes each winter—is sensitive to near-term warming.[225] In Alaska in 2016, active-layer thickness was 4 cm greater than the 1996–2016 average, and three-out-of-four interior sites in Alaska recorded maximum active-layer thickness values.[226] Nordic countries have witnessed a general increase in active layer thickness since 1999.[227] In Siberia, the active-layer thickness recorded the highest thickness in 20 years of observations.[228]

Globally, permafrost harbours about 1,700 Gt of carbon, which is double the amount of carbon in the atmosphere.[229] Of this, 190 Gt of carbon lies within the top 30 cm from the surface, which is most vulnerable to warming.[230] Moreover, half of all carbon in permafrost is within the top three metres of soil.[231] The extent of permafrost line is moving poleward as permafrost in higher latitudes begins to thaw.[232]

Palaeoclimate information on permafrost

During the Palaeocene-Eocene Thermal Maximum (PETM) (about 55 million years ago), Arctic temperatures were more than 10 ºC warmer than today, "causing almost complete loss of permafrost".[233] During the early Holocene (about 12,000 years ago), temperatures in the high latitudes were 2–4 ºC warmer, so a potential tipping point might exist between 4 and 10 ºC, which would be between IPCC scenarios RCP4.5 and RCP8.5.[234] If temperatures increase 10 ºC, the amount of carbon released from the permafrost region could double.[235]

Projections for permafrost

Thawing permafrost is not likely to lead to a sudden change in climate. Rather, a prolonged release of carbon from permafrost will compound upon projected global emissions of greenhouse gases to further contribute to warming.[236] However, feedbacks from carbon dioxide and methane released from thawing permafrost are often not accounted for in the model projections of future climates.[237]

Failure to avoid permafrost thaw jeopardizes the likelihood that climate warming will stay below 2 ºC.[238] Permafrost thaw has already led to the Arctic being an increasing source for carbon emissions.[239] While the Arctic presently serves as a carbon sink, the region could become a carbon source as early as the mid-2020s from the permafrost carbon feedback.[240] Carbon emissions from permafrost will continue for centuries, making the Arctic a long-term net carbon source by the end of the 23rd century.[241] Before that, carbon emissions from permafrost in Siberia and North America could reach 90 Pg C by 2100, which is comparable to present land use contribution to the carbon cycle.[242]

Limiting forcing to more aggressive mitigation scenarios (like RCP2.6) rather than allowing business-as-usual emissions can reduce permafrost degradation by 29%.[243] By drastically limiting emissions as per the RCP2.6 scenario, "85% of the carbon release from the permafrost region can still be avoided".[244] Strong mitigation is essential to limit the permafrost-carbon feedback because even under the 2 ºC warming scenario, up to 22% of permafrost could be thawed by 2100.[245]

There is a large range of possibilities of projected warming from thawing permafrost because of incomplete observational knowledge of permafrost deposits as well as a limitation to modelling the various soil types, soil moisture, vegetation cover, and other surface conditions associated with permafrost thaw.[246] Predictions of permafrost area reductions range from 16–20% in Canada to projections of permafrost area being reduced 40–57%, 60–90%, or even 80–85% in the Northern Hemisphere in other studies.[247] The IPCC states that it is "virtually certain" that near-surface permafrost will be reduced between 37% and 81% in the future as temperatures increase.[248]

Limiting warming to 2 ºC (or less) will make the permafrost-carbon feedback warming negligible whereas allowing business-as-usual emissions and temperature changes will result in additional warming from permafrost of about 0.1 ºC (range of 0.04–0.23 ºC) by 2200 and about 0.42 ºC (range of 0.24–0.78 ºC) in 2300.[249] Under business-as-usual emissions, Arctic near-surface permafrost could decline by 20% (relative to today's area) by 2040 and by about 66% by 2080.[250]

Warming of 1.5 ºC would destroy an additional 4.8 million square kilometres of remaining permafrost, while warming of 2 ºC would see an additional 6.6 million square kilometres thawed.[251] For the RCP scenario that most closely represents the international agreed upon cap of 2 ºC, emissions from thawing permafrost could raise temperatures an additional 0.05 to 0.15 ºC by 2100; 60% of permafrost emissions will occur after 2100 and will jeopardize the 2 ºC target.[252] Under RCP8.5, 33 to 114 Gt of carbon could be released by 2100, which would lead to additional warming of 0.04–0.23 ºC, and under a low-emissions scenario, temperatures remain low enough that only 9–23% of permafrost would be affected and the impact on temperature would be only 0.04–0.16 ºC by 2300.[253]

Nearing the end of the twenty-first century, the extent of permafrost would be reduced to 17.6 million km^2 under RCP2.6, 14.1 million km^2 under RCP4.5, 13.6 million km^2 under RCP6.0, and 8.5 million km^2 under RCP8.5, which amounts to a loss of 25–65% of permafrost extent depending on the scenario.[254]

Costs and non-climate impacts from permafrost thaw

Thawing permafrost can damage built infrastructure that relies on solid ground for support.[255] Roughly four million people within the Arctic and approximately 70% of the current infrastructure is susceptible to being impacted by thawing permafrost.[256] For example, thawing permafrost has already decreased the weight-bearing capacity of building foundations in Siberia by 40–50% since the 1960s.[257] A 2016 study calculated the economic cost of carbon dioxide and methane released from permafrost and found the direct and indirect impacts, not including infrastructure damages, could amount to $43 trillion over the next two centuries.[258]

GREENLAND AND ANTARCTIC ICE SHEETS

This section focuses on the ice sheets of both poles. While the loss of ice impacts the local regions, the ice lost contributes to global sea level rise, impacting coastal locations around the world.

Sea-level rise is accelerating, and sea levels will continue to rise from past, present, and future emissions.[259] Reducing emissions will limit reduce the rate of sea-level rise and also reduce the chance of surpassing crucial tipping points, of which there may exist tipping points for both Greenland and Antarctica between 1.5 and 2 ºC.[260]

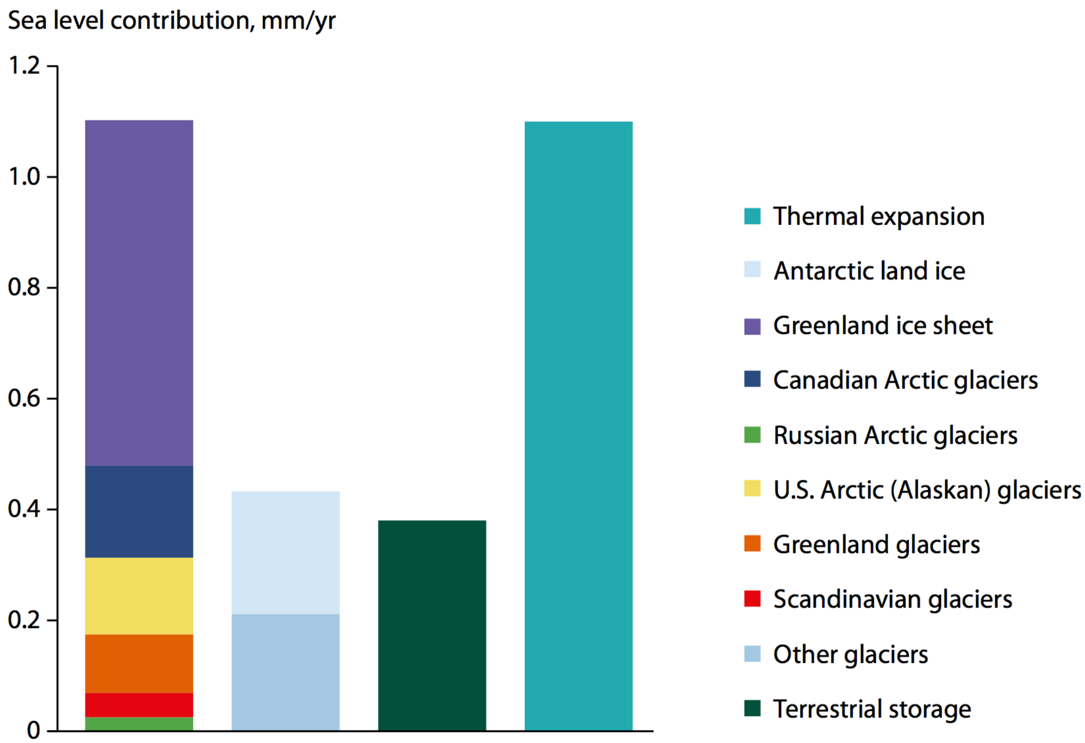
Greenland has experienced accelerated melting in the past few decades, and in recent years, there have been extreme melt events.[261] Over Greenland, there are multiple feedback mechanisms at play that can cause even more melting for the ice sheet. Water from the melting ice can itself accelerate melting.[262] Also, impurities in the ice—from both anthropogenic sources like black carbon deposition and natural sources like algae blooms that are amplified when there is added water on the ice sheet surface—can reduce the reflectivity of the ice and allow greater warming of the surface that will lead to more melting.[263] As melting depletes the ice sheet, its overall elevation decreases, and because temperatures are generally warmer at lower elevations, the surface is therefore warmer that again leads to more melting.[264]

Of the two parts to Antarctica, depletion of the West Antarctic Ice Sheet (WAIS) is the majority of Antarctica's contribution to sea-level rise, though the East Antarctic Ice Sheet (EAIS) overall holds more ice and potential for sea-level rise.[265] The glaciers of the WAIS are already thinning and in retreat.[266] The thinning glaciers are susceptible to increasing water temperatures of the Southern Ocean and major ocean currents that pass through the region, and as the glaciers are worn away, the glaciers become less grounded to the Antarctic land mass, which allows water to get underneath the glacier and more rapidly break the ice into the ocean.[267] Some research suggests that if the WAIS glaciers are not already beyond a tipping point, they are fast approaching a point of no return.[268] If the WAIS were to collapse, sea levels could rise several meters.[269] The EAIS is generally more stable, but the glaciers of the EAIS are similarly vulnerable to increased water temperatures and some showing signs of retreat.[270]

Melting ice sheets of Greenland and Antarctica lead to sea-level rise

The melting of the ice sheets of Antarctica and Greenland pose a global threat due to their contributions to global sea-level rise. Sea-level rise is the result of expansion of the warming water (thermal expansion) and addition of water through melting glaciers (mass balance increase).[271] Approximately one third of SLR is from melting Arctic land ice, primarily from Greenland.[272] From 1971 to 2017, ice from the Arctic region (above approximately 55 ºN) contributed 23.0 ± 12.3 mm of sea level; Greenland contributed 10.6 mm, Alaska 5.7 mm, Arctic Canada 3.2 mm, and Russian High Arctic 1.5 mm.[273] Another third is from thermal expansion of the increased temperature of the ocean.[274] The remaining third from other glaciers and land ice with Antarctica contributing to half of that.[275] *See* Figure 12. In the future, mass loss from glaciers will be the dominating contributor.[276]

Fig. 12: Sources of sea-level contribution



During the period 2004–2010, melting Arctic land ice accounted for more than 1/3 of global sea-level rise, while thermal expansion caused by warming water contributed another 1/3 and contributions from Antarctica, other glaciers and changes in terrestrial storage contributed less than 1/3. (Arctic Monitoring and Assessment Programme (AMAP) (2017) SNOW, WATER, ICE, AND PERMAFROST IN THE ARCTIC: SUMMARY FOR POLICYMAKERS, 4.)

Sea-level rise of the past two centuries has been faster than the previous twenty-seven centuries, and it is extremely likely that anthropogenic warming was a predominant cause.[277] Sea levels rose nearly 20 centimetres between 1901 and 2010.[278] Cumulative emissions of what has already been emitted through 2015 will result in approximately 1.6 metres of global SLR.[279] Future emissions from current energy infrastructure will bring future SLR to 2.2 metres and business-as-usual emissions (RCP8.5) will lead to 7.1 metres of SLR by 2100.[280]

Lower stabilization temperatures—even when there is a temporary overshoot—and reduced rate of warming lead to less sea-level rise during the 21st century.[281] If the goals of the Paris Agreement are met, sea-level rise will be reduced by 43% of the business-as-usual projection by 2100.[282] The Arctic Monitoring and Assessment Programme (AMAP) estimated SLR of 52 cm for a low-emissions scenario and 74 cm for a high-emissions scenario in 2100, both of which are higher than the IPCC projections.[283] Even after temperatures are stabilised, the sea levels can continue to rise as will the risk for extremes events, like storm surge, made worse by raised sea levels.[284]

Fig. 13: Sea-level rise for 1.5 and 2 ºC

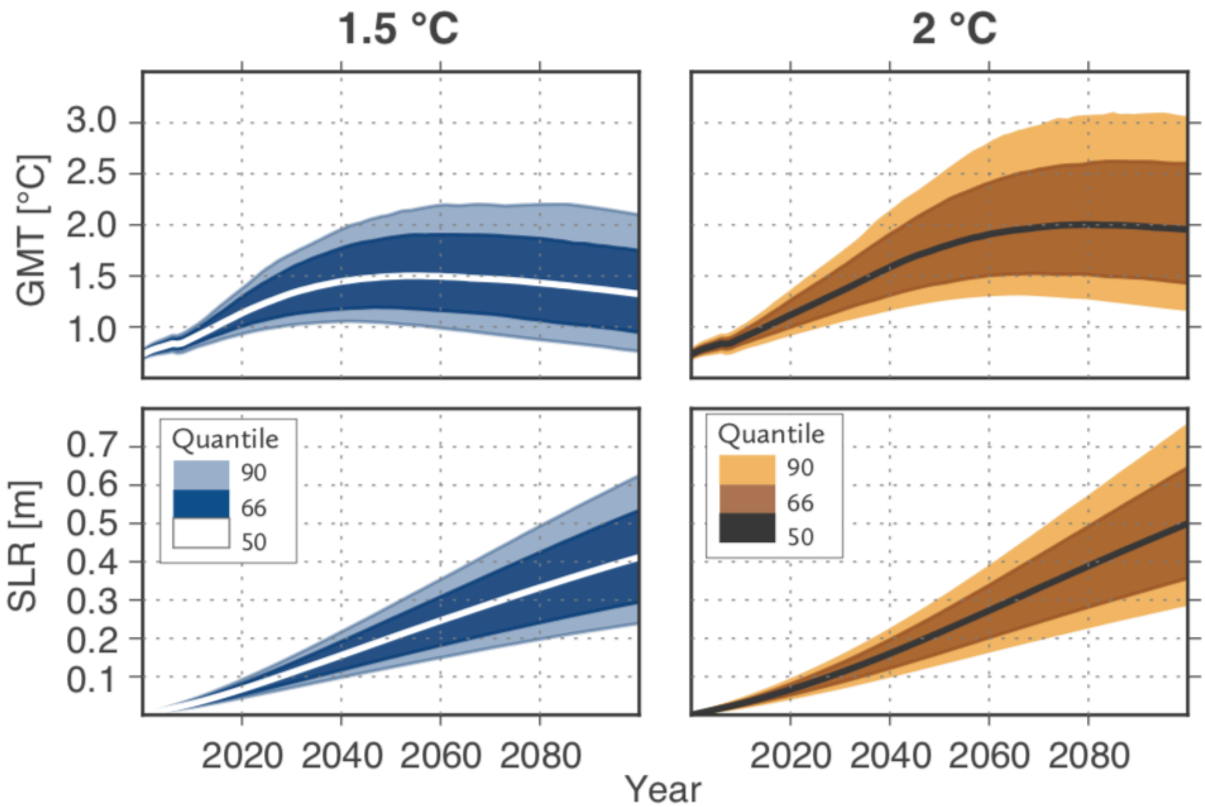


Figure 13. Upper panel: probabilistic GMT projections for illustrative emission scenarios with a peak warming of 1.5 C (left panels) and 2 C (right panels) above pre-industrial levels during the 21st century. Lower panels: probabilistic projections of global sea-level rise (SLR) for both scenarios relative to 1986–2005 levels. Uncertainty bands indicate the likely range (66 % probability within this range) and the very likely range (90% probability), respectively. (Schleussner C.-F., *et al.* (2016) *Differential Climate Impacts for Policy-Relevant Limits to Global Warming: the Case of 1.5ºC and 2ºC*, EARTH SYSTEM DYNAMICS 7:327–351, 341.)

Understanding extreme sea-level rise is important because of the number of people that live in coastal zones, which is currently a population of over 625 million people and likely to increase in the future.[285] With larger average sea-level rise, extreme events relating to sea-level—like storm surge from tropical systems— will likely increase in frequency.[286]

The impacts of sea-level rise include more than general inundation of water and can happen in the near future.[287] For example, low-lying atolls can see routine annual flooding from increased sea levels as early as 2055 with the most extreme emissions scenarios[288] and reduction of available freshwater as early as 2030 for business-as-usual scenarios and 2055 in a climate mitigation scenario.[289]

The thermal-expansion contribution to sea-level rise is influenced by the emission pathway.[290] Sea-level rise relates to the rate of emissions, not just the total emissions.[291] Limiting global average warming to 1.5 ºC instead of 2 ºC leads to 17 cm less SLR by 2150 and reduces rate of SLR by 1.9 mm/yr.[292] As such, climate policies should not exclusively focus on cumulative carbon emissions but on the rate of warming, which is influenced by all emissions, including short-lived climate pollutants (SLCPs).[293] Reversing sea-level rise requires reducing radiative forcing, with negative forcing (through carbon removal) speeding up the process.[294]

With the current rate of emissions, the melting of land-based ice in the Arctic would add 25 centimetres of sea-level rise by 2100 with many of the smallest glaciers gone by mid-century.[295] Sea-level rise under a 2 ºC scenario is projected to be around 50 cm (36–65 cm) by 2100, which equates to a rate of rise of 5.6 (4–7) mm/yr during the last two decades of the century.[296] When temperatures are held to 1.5 ºC, sea-level rise projection is 20% less, and the end-of-century rate of SLR is decreased by 0.5 mm/yr.[297] However, sea levels could well exceed these values if the ice sheets become unstable, which would allow greater disintegration of the ice into the ocean.[298]

Fig. 14: Sea-level rise contributions from Greenland and Antarctic

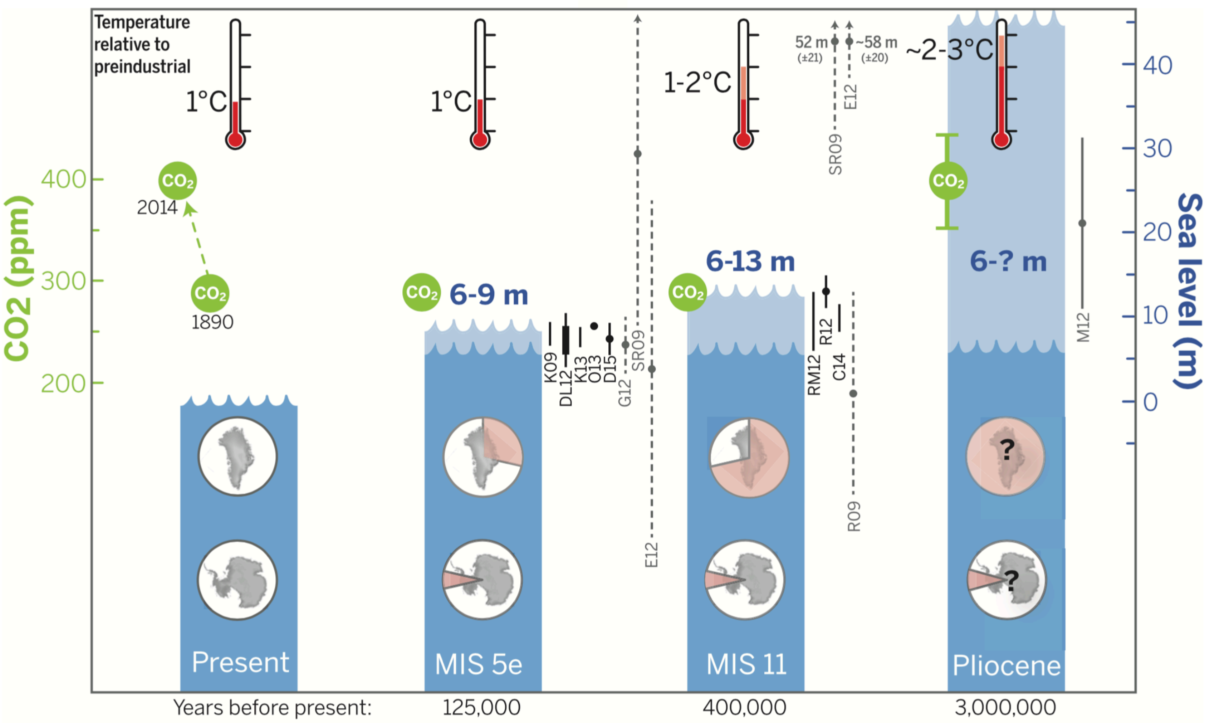


Fig. 4. Peak global mean temperature, atmospheric CO_2, maximum GMSL, and source(s) of meltwater. Light blue shading indicates uncertainty of sea-level maximum. Black vertical lines represent GMSL reconstructions from combined field observations and GIA modeling; gray dashed lines are $\delta^{18}O$-based reconstructions. Red pie charts over Greenland and Antarctica denote fraction (not location) of ice retreat. Although the peaks in temperature, CO_2, and sea level within each time period may not be synchronous and ice sheets are sensitive to factors not depicted here, significantly higher sea levels were attained during MIS 5e and 11 when atmospheric CO_2 forcing was significantly lower than present. See tables S3 and S4 for data and sources. (Dutton A., *et al.* (2015) Sea-level rise due to polar ice-sheet mass loss during past warm periods, SCIENCE 349(6244):aaa4019-1–aaa4019-9, aaa4019-5.)

Tipping points for both Greenland and Antarctica exist between 1.5 and 2 ºC, possibly leading to irreversible ice loss from Greenland and collapse of parts of the Antarctic ice sheet as a consequence of weaker ice shelves.[299] The totality of the changes to the ice sheets of Greenland

and Antarctica will not be realised for centuries or even millennia yet the threshold for triggering these irreversible changes could like be surpassed within this century.[300]

Once ice sheets become destabilized, they have the potential to add several metres of sea-level rise. To understand what melting ice sheets might contribute to sea-level rise, we must first understand the mechanisms through which they are most vulnerable. For example, for the Antarctic ice sheet, scientists must determine "which marine-based sectors are most vulnerable to collapse and [identify] the forcing (atmospheric or oceanic) that would trigger such events."[301] By looking at the last glacial period, scientists evaluated the mechanism through which abrupt discharges of icebergs can occur,[302] finding that warm ocean water can amplify the ice disintegration from underneath.[303] This could provide insight into how current atmospheric and oceanic warming can impact ice sheets.[304]

Much of the understanding of the sensitivity of the Antarctic to warming temperatures comes from evaluation of the Pleistocene and other warmer eras of the past,[305] when sea levels were 6–9.3 m higher than today even though global temperatures were only slightly warmer.[306] Only about 0.4 m of sea-level rise came from ocean steric effects (thermal expansion), which suggests that Antarctic contributed 3.6–7.4 m of sea-level rise and Greenland another 1.5–2.0 m.[307]

GREENLAND

Recent observations

The threshold for irreversible melting of the Greenland Ice Sheet is global averaged temperature of 1.6 ºC, with a potential tipping point for complete melting of the ice sheet at 3.1 ºC.[308] Observations show that since the mid-1990s Greenland has warmed by about 5 ºC in winter and 2 ºC in summer, and at the same time, the ice sheet has increasingly lost mass from surface melt, runoff, and ice discharge.[309] Since the mid-1990s, increasing ice discharge and decreasing surface mass have led to the Greenland ice sheet being the dominant source of mass-increase-based sea-level rise, contributing roughly 0.47 mm/yr.[310]

Greenland has experienced intensification in surface melt in recent years,[311] some of which was driven by natural climate variability[312] but with an unprecedented increase in this trend beginning in 2007.[313] Between 2011 and 2014, Greenland lost an average 375 Gt of ice per year, twice the rate seen from 2003 to 2008.[314]

The Greenland ice sheet had relatively low summer ice melt in 2017, which corresponds to relatively high albedo over the ice sheet and near average net ice mass loss.[315] In 2018, surface melt over Greenland was only above average for about one quarter of the summer months, which is above 2017's low-melt year of 16% of days above average.[316] The albedo in 2018 was 81.7% through June through August of 2018, which was the tied for the lowest summer albedo since 2000.[317] However, this does not take away from the overall melting trends seen in last few decades over Greenland.

Feedbacks and accelerated melting in Greenland

With Arctic amplification, not only are temperatures in higher latitudes warmer—which affect the melt rate on the Greenland—, the warmer Arctic alters the general atmospheric flow[318] that results in enhanced warming over Greenland.[319] Furthermore, climate change has affected atmospheric circulation over Greenland[320] in such a way that cloud cover has decreased,[321] which has added solar radiation and contributed to additional surface melt.[322]

Because of rising temperatures, Greenland's peripheral glaciers and ice caps have suffered increased surface runoff and mass loss due to the decreasing ability of the firn—porous snow that has yet to compressed into glacial ice—to refreeze the meltwater.[323] The porous firn in Greenland can trap the meltwater of higher elevations before the meltwater can contribute to runoff, but surface runoff can overwhelm firn's storage ability at lower elevations where the firn has less ability to retain meltwater.[324]

Ice-sheet runoff in Greenland increased in 2003–2014, compared to 1976–2002, which is likely the result of changing atmospheric circulation from climate change.[325] Increased melt-water runoff and ice discharge from Greenland's ice sheet accounted for 0.6 mm/yr of SLR, with melt-water runoff accounting for 60% and ice discharge for 40%.[326] Achieving peak warming this century is the best way to maintain the present state of the Greenland ice sheet.[327]

The Greenland ice sheet was relatively stable from the mid-20th century until 1990, after which the glacier began to lose mass at an increasing rate.[328] Greenland ice cores revealed a 250 to 575% increase in melt intensity in the last two decades.[329] These most recent melting events are beyond that of natural variability and more dramatic than others in the past 350 years.[330] Future changes to the Greenland ice sheet will likely stem from a combination of increasing temperatures facilitating melting[331] and non-linear responses—where the melting exceeds what may have otherwise been expected from the amount of warming—from the ice-albedo feedback of surface meltwater amplifying the speed that the ice melts.[332] Retreating ice sheets could also lead to taller ice cliffs that are susceptible to slumping and sudden failure that can rapidly raise sea levels when the ice enters the ocean.[333]

On the surface of Greenland, light-absorbing impurities—like black carbon or biological material—reduce the albedo, which accelerates melting of surface snow and exposes the ice underneath that in turn reduces surface albedo because ice is less reflective than snow.[334] Albedo can also be altered by naturally occurring algae that is prevalent during the initiation of melting.[335] These algae blooms can reduce local albedo by up to 20%, contributing to added melting in the area that can expedite algae growth.[336] As melting is one of the main causes of the algae growth, these blooms will become more frequent with a greater occurrence of melting events, like the one in 2012.[337]

Melting on Greenland's surface is going to continue in the coming decades, which will perpetuate the darkening of the surface by revealing the underlying ice.[338] On some areas of the Greenland ice sheet, algae growth facilitates more surface melting than black carbon.[339] Deposition of light-absorbing impurities on the Greenland ice sheet has not been increasing in recent years,[340] but as Greenland continues to melt, previously deposited impurities are being exposed and further enhancing melting.[341] As such, any additional deposition of these impurities—for example, from emissions as a result of increased shipping and transportation within the Arctic region—will also accelerate this already perilous situation. [342]

Greenland is affected by other feedback mechanisms the ice-albedo feedback.[343] As Greenland melts, the ice sheet loses elevation, which can instil further warming because temperatures are warmer at lower elevations; this is the surface elevation feedback that is relatively small compared to other changes on the ice sheet but can still have an impact on sea-level rise.[344] Melting in Greenland can be affected by increased temperature but also from seasonally modified feedback from precipitation falling as rain instead of snow during the winter[345] as well as increased humidity and clouds in the region that trap in additional warming near the surface during both winter and summer.[346]

Greenland's palaeoclimate and associated sea-level rise

To get an understanding of the potential changes that could happen with the Greenland Ice Sheets, scientists have turned to palaeoclimate records to investigate how the ice sheet has changed in the past. Some of the most striking rapid warming events in the palaeoclimate record—Dansgaard-Oeschger events[347]—may have been partially attributed to a decline in Arctic sea ice that surrounds Greenland.[348]

In December 2016, two studies were released with seemingly contrasting analyses of Greenland's past. In Bierman *et al.* 2016, the authors found that the Greenland ice sheet existed continuously over the past 7.5 million years on the eastern side of the island.[349] In contrast, Schaefer *et al.* 2016 found that during the Pleistocene (between 11,700 and 2,588,000 years ago) only a small ice cap remained on the eastern highlands of Greenland, which means that more than 90% of the Greenland Ice Sheet had melted.[350]

Duration and amount of warmth influences the stability of the Greenland Ice Sheet as well as its potential for deglaciation; extreme temperature reduces the ice sheet within a few thousand or even several hundred years.[351] The model used in the Schaefer *et al.* 2016 study revealed that the Greenland ice sheet was almost completely absent for a period of time in the Pleistocene, which is incompatible with existing ice-sheet models, implying that further analysis into the climate-driving scenarios is necessary to replicate the deglaciation.[352]

Fig. 15: Geography of Antarctica—glaciers, ice shelves, ice streams, and basins

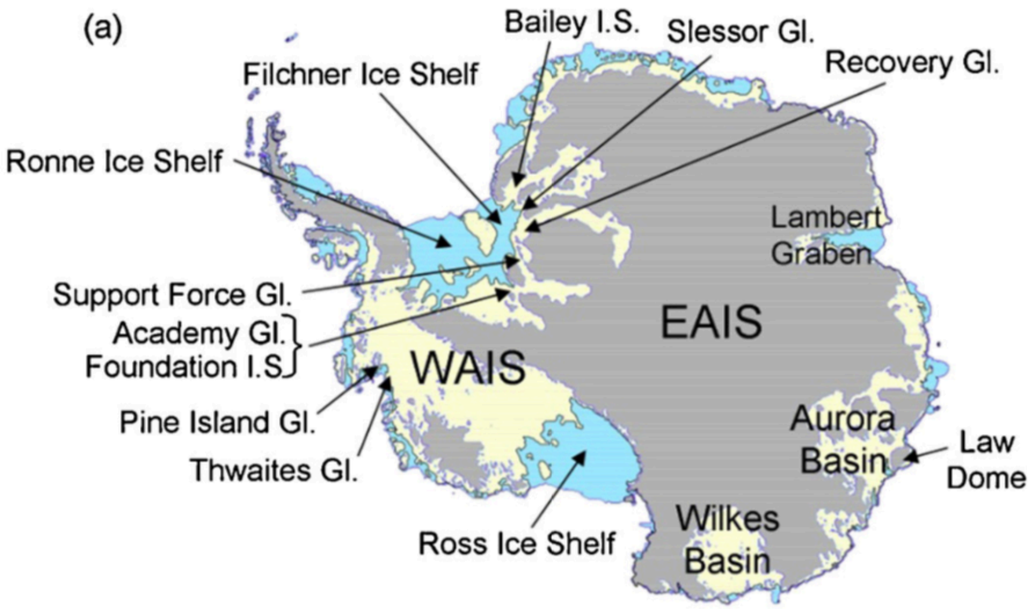


Fig. 1. Antarctic location map and modern properties. (a) Locations of features named in the text. EAIS = East Antarctic Ice Sheet, WAIS = West Antarctic Ice Sheet, I.S. = ice stream, Gl. = glacier. Yellow shading shows the areas of grounding line retreat after 5000 yr in the main retreat simulation of Fig. 3, and cyan areas are modern floating ice shelves. (Pollard D., *et al.* (2015) *Potential Antarctic Ice Sheet retreat driven by hydrofracturing and ice cliff failure*, EARTH & PLANETARY SCIENCE LETTERS 412:112–121, 113.)

West Antarctic Ice Sheet (WAIS)

In recent years, mass loss from Antarctica has accelerated, mainly from the Antarctic Peninsula and West Antarctica.[353] Glaciers that flow into the Amundsen Sea (on the west coast of West Antarctica) have thinned, suggesting that unstable and irreversible retreat of the groundling line is underway.[354] Researchers have surmised that the Pine Island Glacier's grounding line is "probably engaged in an unstable…retreat," which has led to an equivalent of 3.5 to 10 mm of sea-level rise to be seen in the next twenty years.[355]

The glaciers in West Antarctica that feed into the Amundsen Sea are rapidly thinning and are the largest contributors to sea-level rise from Antarctic sources.[356] In the past four decades, the Pine Island Glacier and other glaciers in the area have thinned at an accelerating rate.[357] The Pine Island Glacier is responsible for 20% of total ice discharged from West Antarctica.[358] Observations have shown that the Pine Island Glacier retreat, which is potentially irreversible, is projected to continue for at least the next century.[359] Similarly, the Thwaites glacier may also already be destabilised, making rapid collapse a possibility, even if it takes centuries to fully to come fruition.[360]

Hypotheses about the cause of the continued retreat range from ice-ocean interactions to a retreating grounding line.[361] The grounding line is the point where a glacier begins to float as an ice shelf.[362] Channel density, basal-melt rate, and grounding line depth alterations could create destabilization of the West Antarctic ice sheet through increased access to warmer water beneath the ice shelves that would increase calving and reduce ice shelf area.[363]

Circumpolar Deep Water is responsible for creating the basal channels whereby the relatively warmer water (when compared to the temperature of the ice) influences the melt rates of the ice shelves surrounding the Amundsen and Bellingshausen Seas.[364] As the ice shelves become thinner, they provide less resistance for the ice flowing to the ocean, leading to accelerating ice deposition into the sea and increasing rates of sea-level rise.[365] The warmer water seeps underneath the ice shelves and facilitates more rapid melting that can lead to ice fracture and weakened ice shelves.[366]

The Pine Island Glacier melt is accelerating from sub-ice-shelf melting.[367] Ocean-driven melt can greatly influence grounding-line retreat and thus the stability of ice sheets, but when atmospheric concentrations of greenhouse gases lead to excessive warming, atmospheric warming becomes a larger player in ice sheet demise.[368] Because ice shelves help impede the flow of ice into the sea and stabilize the grounding zones, the retreat of these shelves can trigger runaway instability.[369]

The WAIS appeared to achieve stability between 2009 and 2013, but in 2014 and 2015, anomalous rifts appeared that "initiated in the centre of the ice shelf and propagated toward the margins."[370] These recent splits in the ice sheet are different than the typical style of ice shelf rifting because it begins in the centre of the fast-flowing ice shelf.[371]

Using sediment cores, a 2017 study found that the thinning and retreat of the Pine Island Glacier in West Antarctica was triggered in the 1940s and enhanced by subsequent warming such that the ice sheet retreat continued even after the climate forcing weakened.[372] El Niño conditions between 1939 and 1942 led to warming in West Antarctica in the years that followed, and it was during this time that an ocean cavity appeared and caused the groundling line retreat that eventually unpinned the Pine Island Glacier ice shelf in the early 1970s.[373] The implication of this study is that the warming in the 1940s began a chain of events that perpetuated ice shelf thinning long after the warming had subsided and conditions returned to normal, suggesting that "ice-sheet retreat can continue even when the forcing reverts to its earlier state."[374]

As individual glaciers collapse, unstable conditions could easily propagate throughout the basin and sow instability for the entire ice sheet.[375]

East Antarctic Ice Sheet (EAIS)

The Totten Glacier in Antarctica is crucial to the climate system because it is the largest discharger of ice in East Antarctica.[376] While the grounding line retreat of the Totten Glacier is smaller than that of the Amundsen Sea sector of the West Antarctic, the Totten Glacier holds four times the amount of sea-level equivalent such that "any amount of grounding retreat of [Totten Glacier] may still bare significant consequences for sea-level rise from Antarctica."[377] If all of the ice in the Totten Glacier were to melt, it would contribute 3.9 m to global sea level.[378]

The grounding line of the Totten Glacier in Antarctica retreated by 1–3 km from 1996 to 2013, which suggests that the ice is "flowing faster than the speed required to maintain a state of mass balance with snowfall in the interior region."[379] These changes are likely the result of forcing from the warmer ocean water that is fuelling high melt rates in the region.[380]

Studies have shown that Circumpolar Deep Water has contributed to glacier retreat in West Antarctica, and researchers have found that a similar process could disrupt the Totten Glacier in East Antarctica, potentially contributing 3.5 metres of sea-level rise, which is almost equivalent to the sea-level rise potential from the total of the West Antarctic Ice Sheet.[381] The Totten Glacier is important to ice sheet discussions because it has the fastest thinning rate of glaciers in East Antarctica.[382] The Totten Glacier may be strongly sensitive to ocean temperatures given that it has steadily been losing mass over the past twenty-six years due to a speeding up of its main flow.[383]

Winds travelling down the slopes of Antarctica's mountains warm the surface and contribute to snow erosion, amplifying surface warming by revealing the lower-albedo ice beneath the snow layer.[384] Based on observational records, increased temperatures and reduced firm storage—similar to that seen in Greenland—are projected to occur more frequently in the future and amplify this feedback risk on the ice shelf of East Antarctic ice sheet.[385]

Sea-level rise contribution from Antarctica

Limiting warming to 1.5 or 2 ºC will prevent substantial loss of Antarctic ice, and as such, emissions of the next few decades will have heavy influence on the long-term changes to Antarctica.[386] Since 1979, the West Antarctic Ice Sheet has contributed 6.9 ± 0.6 mm of sea-level rise[387] and East Antarctic Ice Sheet has contributed 4.4 ± 0.9 mm of sea-level rise.[388]

Using an ice sheet dynamics model that reflected the changes to Antarctica during the Pliocene and the Last Interglacial, DeConto and Pollard (2016) calculated that Antarctica could contribute more than a metre of sea-level rise by 2100 if emissions are not curbed, while also showing potential sea-level rise of half a metre for other scenarios.[389] Incorporating this palaeoclimate information with IPCC projections, Antarctica did not contribute to sea-level rise by 2100 for RCP2.6, but for RCP4.5, sea level rose 32 cm by 2100 with almost complete collapse of the West Antarctic Ice Sheet by 2500, which produces nearly 5 m of sea-level rise.[390] Under RCP8.5, sea levels rose 77 cm by 2100 and the WAIS collapsed within 250 years.[391]

Grounding lines are important to the stability of the Antarctic glaciers, and recently, the pace of retreat of the grounding lines has been increasing.[392] Thinning ice shelves in the Antarctic can impact the entire ice shelf by accelerating overall ice flow.[393] Pollard *et al.* (2015) found that hydrofracturing from surface melt could enhance draining into ice-sheet crevasses and weaken the grounding lines, which limits the buttressing abilities of the ice sheet and leads to accelerated ice sheet retreat and collapse that can lead to approximately 17 m of global sea-level rise.[394] EAIS collapse is connected to temperature increase because the grounding line is above sea level and the ocean warming does not have as strong of an impact.[395] However, the WAIS undergoes major collapse with 2 ºC of ocean warming and several hundred to a thousand years of impact on the grounding lines.[396]

Antarctic sea ice

In addition to forming in opposing seasons, Antarctic sea ice is vastly different from Arctic sea ice. While the Arctic is a large ocean surrounded by land masses, Antarctica is a large land mass surrounded by water, and as such, the sea ice that forms is not bounded and is therefore free to float to warmer water, which leads to Antarctic sea ice melting nearly every year in stark contrast to the Arctic's multi-year ice.[397] For similar reasons, Antarctic sea ice is not as thick as Arctic sea ice.[398] Antarctic sea ice is also more susceptible to melting from solar radiation than Arctic sea ice because Antarctic sea ice only extends to about 75 degrees south latitude whereas the Arctic sea ice frequently extends further equatorward.[399]

In contrast to the repeated record lows for Arctic sea ice extent, the Antarctic sea ice set a record maximum in September 2014, surpassing the previous record by about 0.5 million square kilometres.[400] In September 2017, the Antarctic sea ice reached its maximum earlier than usual and has been at record or near record lows since September 2016.[401] In 2018, the Antarctic sea ice reached its maximum extent later than usual,[402] and it was the fourth lowest maximum extent in the satellite record, measuring 18.15 million square kilometres (180,000 square kilomteres above the record low.[403]

Antarctic sea ice hit a record low for minimum sea ice extent in March 2017, extending 2.11 million square kilometres,[404] which is 740,000 square kilometres below the 1981–2010 average.[405] During this time, air temperatures were between 1.0 and 2.5 ºC above the 1981–2010 average.[406] That year, the Antarctic sea ice extent began its regrowth but to a lesser extent than the long-term record due to warmer-than-average sea surface temperatures.[407] In 2019, the Antarctic sea ice minimum was reached on both 28 February and 1 March 2019 and was the seventh lowest on record, reaching an extentof 2.47 million square kilomets.[408]

LONG- AND SHORT-TERM PRIORITIES AND SOLUTIONS

This section addresses the priorities and solutions for protecting the Polar Regions. The priorities relate to general actions that must be taken to slow warming while the solutions present specific examples of what can be done to mitigate climate change.

The first priority is to reduce short-lived climate pollutants (SLCPs) because they have the potential to slow the rapid pace of warming and avoid surpassing crucial tipping points. The second priority is to achieve long-term climate stability through CO_2-focused mitigation. The third priority is carbon dioxide removal (CDR), which has the potential to limit the likelihood of catastrophic and existential threat by removing excess carbon from the atmosphere.

The solutions presented here cover a range of suggestions to slow the rate of warming and reduce future warming overall. The solutions encompass many laws and policies that can encourage transition to more sustainable future. This Primer will focus on reducing SLCPs because of their ability to reduce near-term warming and the current climate being precariously close to offsetting self-reinforcing feedbacks and tipping points in the Polar Regions.

PRIORITIES

Securing long-term climate stability through a three-lever approach
The climate must be stabilized well below 2 ºC—aiming for 1.5 ºC—to ensure long-term climate stability. Committed warming may already be as high as 2.4 ºC, but aerosols provide cooling such that only approximately 1.0 ºC of warming has been observed.[409] The Arctic is already twice as warm as the global average,[410] and Arctic amplification is poised to become stronger in the future, which will have impacts within and beyond the Arctic.[411] Following business-as-usual practices, warming could exceed 1.5 ºC within decades.[412]

To fully stabilize the climate, emissions of both SLCPs and CO_2 must be drastically reduced, and to increase the odds of avoiding catastrophic warming, we must also extract carbon from the atmosphere.[413] The benefits of SLCP mitigation will be felt within decades, but past and present CO_2 emissions will continue to cause warming through this century and beyond because of CO_2's long lifetime and the thermal inertia of the oceans.[414] Fast action on these first two levers must happen as quickly as possible to meet the Paris Agreement targets and to avoid surpassing tipping points and triggering self-reinforcing feedbacks; carbon dioxide removal, as the third lever, will help compensate for carbon emissions.

Greenhouse gas emissions do not have to become net zero to achieve 1.5 or 2 ºC of warming, so long as mitigation measures are incredibly drastic and rapid, with total emissions falling to 10 $GtCO_2$-eq per year around 2033 to stay below 1.5 ºC of warming and 16 $GtCO_2$-eq per year around 2060 to stay below 2 ºC of warming.[415] However, these reductions to total GHGs still demands net zero CO_2, though that is easier to achieve because it demands far less negative CO_2 emissions.[416]

Achieving near-term success through SLCP mitigation
Near-term reductions in emissions of SLCPs, particularly black carbon and methane, are crucial to slowing the pace of warming in coming decades[417] and stabilizing the Arctic and Antarctic.[418] Cutting black carbon and methane can decrease the rate of global warming by half[419] and overall warming in the Arctic by two-thirds.[420]

Reductions of CO_2 would avoid 0.1–0.3 ºC of warming by 2050 and 1.6–1.9 ºC by 2100.[421] Reducing SLCPs yields quick results in the crucial near-term, avoiding 0.6 ºC of warming by 2050 and 1.2 ºC by 2100.[422] Approximately half of the avoided warming in 2050 from reducing SLCPs and 40% of the 1.2 ºC avoided warming at 2100 can be accomplished with CO_2-dedicated measures.[423]

Carbon neutrality must be achieved by mid-century
Carbon neutrality—zero anthropogenic CO_2 emissions such that no additional CO_2 is added to the atmosphere—must be achieved by 2060–2070 to attain a stable climate. This can be done through reducing energy intensity and decarbonisation of the energy sector. Overall, cumulative emissions of CO_2[424] must be limited to 3.7 trillion tonnes.[425] At the current pace of emissions, this budget could be exhausted by 2030.[426]

Existing carbon-intensive infrastructure will not vanish overnight, and as a result it will take decades before sufficient infrastructural changes are able to achieve carbon neutrality.[427] Fossil fuel infrastructure and the policies in place to facilitate the infrastructure create a carbon lock-in where a future transition to low-carbon alternatives is more costly in the long term.[428] Making a future switch to low-carbon technology requires these conventional technologies to be retired early, which adds to the cost.[429] This is because fossil fuel infrastructure, like coal-fired power plants, has a multi-decade lifetime.[430] Research has shown that extensive proliferation of renewable energy sources—wind and solar, primarily—can be utilised to provide a substantial portion of the energy sector, approaching 80% within decades.[431]

Renewables had the highest growth rate of all energy sources for 2017,[432] with China and the U.S. contributing about half of increase in renewable energy generation.[433] Overall in 2017, global energy demand increased by 2.1%, which is more than double the average increase of the previous five years, and roughly 40% of this growth was from China and India.[434] Between 2014 and 2016, energy-related CO_2 emissions remained flat, but in 2017, emissions grew by 1.4%.[435] This increase in energy related CO_2 emissions comes from an increase in overall demand—especially electricity demand—and slowed improvements to energy efficiency.[436] Electricity demand increased, of which China and India made up a majority.[437] Energy efficiency improvements were slowed in 2017 because of weaker policies and lower energy prices.[438]

Avoiding catastrophic climate threat with carbon dioxide removal (CDR)
Absent carbon removal strategies, the carbon neutrality and super pollutant levers will only be able to limit the 50% probability warming to below 2ºC while still risking dangerous warming in both the near-term and long-term.[439] Beyond looking at the 50% probability of passing a temperature target, there are lower-probability (5%) but higher-impact warming possibilities,

which consider uncertainties of future emissions, self-reinforcing climate feedbacks (water vapor, clouds, and snow/ice albedo), carbon cycle feedbacks (decrease in land/ocean uptake, soil carbon release from permafrost, and carbon emissions from wetlands), and aerosols.[440] This 5% probability—a 1 in 20 chance—is referred to as the “fat tail”. Carbon dioxide removal strategies could pull down sufficient CO_2 from the atmosphere to limit the likelihood of the climate warming into this “fat tail” range.[441]

Combined with SLCP and CO_2 mitigation, CDR will limit cumulative emissions such that there is a 50% chance of staying under 1.5 ºC, reducing the likelihood of catastrophic warming in the long-term.[442] More rapid mitigation will require less CDR to maintain a safe climate.[443]

SOLUTIONS

Maintaining a safe climate requires fast-action mitigation of both SLCPs and CO_2.[444] Mitigating SLCPs is not a substitute for CO_2 mitigation as both are necessary for keeping warming below 1.5 ºC. Some CO_2 will remain in the atmosphere for several millennia,[445] with approximately a quarter of CO_2 emissions lasting more than 500 years.[446] Furthermore, the added warming from reducing sulphates can be offset by reduction in methane and black carbon.[447]

Mitigation measures to reduce SLCPs

SLCP emissions can be quickly reduced through existing technologies, laws, and institutions. The United Nations Environment Programme (UNEP) & World Meteorological Organization (WMO) (2011)[448] and Shindell *et al.* (2012)[449] provided examples of potential measures for curbing black carbon and methane emissions, and these measures are summarized below.

With extensive implementation of the mitigation measures for methane and black carbon, 38% of global methane and 77% of global black carbon emissions can be eliminated.[450] If the above measures were implemented by 2030, future warming would be reduced by 0.5 ºC globally, which would amount to reducing warming in the Arctic by two-thirds in the next thirty years.[451] Additionally, these measures can prevent losses to staple crops and avoid millions of premature deaths worldwide.[452] Notably, the regions making reductions in black carbon and tropospheric ozone get most of the benefits.[453]

Methane-control measures include:

- Pre-mine degasification, recovery, and oxidation of methane from ventilation air from coal mines;
- Recovery and utilisation (instead of venting) of gas and fugitive emissions from oil and natural gas production;
- Reduce leakage from long-distance natural gas transmission and distribution;
- Landfill gas collection;
- Upgrade wastewater treatment with gas recovery and overflow control;
- Decrease livestock emissions through animal feed and manure management; and
- Intermittent aeration of continuously flooded rice paddies.

Black-carbon control measures include:

- Improve diesel vehicle emissions standards and install diesel particulate filters;
- Replace traditional cooking and heating stoves with clean burning modern fuel stoves;
- Replace brick kilns with vertical shaft and Hoffman kilns;
- Replace traditional coke ovens with modern technologies, including end-of-pipe abatement measures;
- Eliminate high-emitting on- and off-road diesel vehicles;
- Ban open burning of agricultural waste; and
- Replace kerosene wick lamps with modern clean lighting technologies.

The Arctic Council Expert Group on Black Carbon and Methane developed a similar list of recommendations for reducing emissions of black carbon and methane.[454] Recommendations from the Expert Group include: reducing black carbon emissions from diesel powered mobile sources through policies and initiatives that encourage particulate filters and alternative fuels[455]; reducing methane and black carbon emissions from leaking, venting, and flaring from the oil and gas sector[456]; reducing black carbon emissions from biomass combustion appliances, including employing energy efficiency measures and incentivizing replacement of older appliances[457]; and avoiding methane emissions associated with solid waste disposal.[458]

Arctic States could lead by example in reducing emissions of black carbon and methane.[459] As noted above, Arctic States account for ten per cent of the global emissions of black carbon but nearly a third of the warming in the Arctic.[460] For methane, Arctic States account for about fifth of the global emissions, but also have the largest potential for abatement of emissions.[461]

Methane is a well-mixed GHG, which makes it difficult to pinpoint the exact source, but this also means that global reductions will still help the Arctic region.[462] The main source of methane include: fossil fuel production, transmission, and distribution; livestock; rice cultivation; and solid waste and wastewater.[463] As a precursor for tropospheric ozone, methane is responsible for approximately half of the radiative forcing from tropospheric ozone, and reducing methane will decrease the overall forcing of tropospheric ozone, especially in the Arctic where distant methane emissions contribute to the formation of tropospheric ozone.[464]

Reducing SLCP emissions from diesel engines may be one of the simplest and most effective ways to mitigate near-term climate forcing.[465] California has already accomplished decreased concentrations of black carbon reductions of 50% between 1989 and 2008 through a reduction in emissions from diesel fuel.[466] On-road and non-road mobile sources accounted for 61 per cent of black carbon emissions in the Arctic States, which can be curbed through a myriad of policies, including: emissions standards for new vehicles; programs targeting the replacement or upgrading of legacy vehicles; standards to reduce sulphur levels in fuels and enable usage of diesel particulate filters; and alternate fuels and transportation methods that will reduce emissions overall.[467]

Improvements within the domestic heating and cooking sectors throughout Asia would cut black carbon and have the largest impact on the Arctic.[468] Kerosene-fuelled wick lamps are a significant source of black carbon and can be replaced with affordable alternatives that are available now.[469] Eliminating emissions of black carbon from traditional solid biomass stoves by replacing them with improved cook stoves would reduce black carbon direct climate effects over South Asia by about 60%.[470]

Most of the control measures to reduce black carbon and tropospheric ozone—and its precursor, methane—can be implemented immediately using existing technologies and often using existing laws and institutions.[471] Half of the identified mitigation measures for SLCPs can be implemented with a net cost savings for those making the investment.[472] The benefits of reducing emissions of methane are valued at up to $5000 per metric ton, which is substantially higher than the typical abatement cost of less than $250.[473]

Additionally, certain strategies that reduce CO_2 will also reduce SLCPs. For instance, switching to renewable energy sources will reduce methane and tropospheric precursors like carbon monoxide and nitrogen oxides that are emitted during fossil fuel consumption and production.[474] Some 70% of methane emissions and 30% of black carbon emissions can be mitigated through CO_2-targeting actions.[475]

While many emissions-reducing measures can provide a net cost savings alongside significant societal and health benefits,[476] some policies will require overcoming financial implementation barriers.[477] Economic incentives can stimulate voluntary action to upgrade engines and fuels or even facilitate full replacement.[478] Combined use of diesel particulate filters and low-sulphur fuel has proven "highly effective, net beneficial, and widely adopted across most participating countries".[479] These policies "can nearly eliminate black carbon emissions" but can be costly because of the need to upgrade refineries and maintain fuel distribution chains to avoid contamination with high-sulphur fuels.[480]

Co-benefits from SLCP reductions

Reductions in emissions of SLCPs have other benefits besides the direct climate benefits.[481] For example, reducing black carbon will not only help avoid climate warming, but as a component of particulate matter—a harmful air pollutant—reducing black carbon will also lead to improved air quality.[482]

According to the World Health Organization (WHO), there is no safe level of exposure to fine particulate matter, of which black carbon is a component.[483] Air pollution was responsible for 7 million deaths worldwide in 2012, and most of those deaths occurred in the Western Pacific and South East Asian regions.[484] Of these deaths, 3.7 million were from ambient air pollution[485] and 4.3 million from household air pollution, with some one million deaths attributable to a combination of the two.[486] If air pollution is not curtailed, premature deaths could double by 2050.[487]

In the U.S., air pollution mitigation yielded an estimated $30 in benefits for every dollar spent on air pollution controls since 1970, for a total of $1.5 trillion in benefits for the $65 million invested.[488] Since the passage of the Clean Air Act, the U.S. has reduced six common air pollutants by 70% while, at the same time, GDP has risen 250%.[489]

In addition to reducing the rate of warming, reducing SLCPs will reduce the rate of sea-level rise (SLR) by 18% by 2050 and 24% by 2100, compared to a baseline of business-as-usual; reducing CO_2 will have a negligible effect mid-century but will reduce the rate of SLR by 24% in 2100.[490] Cumulative SLR at 2100 is reduced 31% with both CO_2 and SLCP mitigation measures, with most of the reduction coming from SLCP mitigation.[491] *See* Figure 16.

Methane mitigation would have the greatest impact in slowing SLR, followed by CO_2 and then the other SLCPs.[492] Delaying mitigation of SLCPs until 2040 will decrease the impact of both CO_2 and SLCP mitigation on SLR this century by approximately 30%.[493] As mentioned earlier, slowing the rate of warming also slows the rate of sea-level rise because of the thermal expansion component to SLR.[494]

Fig. 16: Predicted reductions in 21st century sea-level rise due to SLCP and CO_2 mitigation

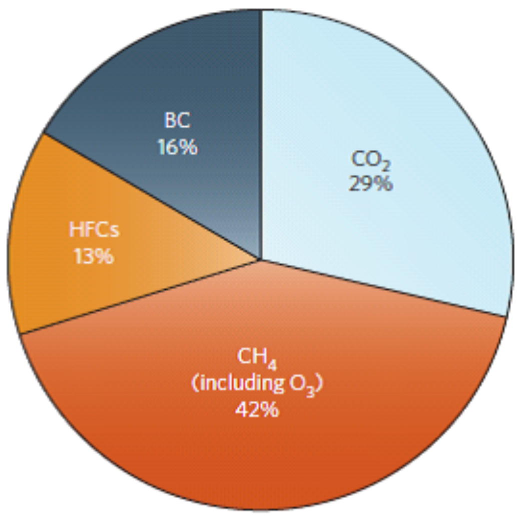


Figure 1. Avoided sea-level rise at 2100 due to aggressive mitigation of long-lived CO_2 and SLCPs. Such aggressive actions can reduce the rise in sea levels by 35 cm (uncertainty range is 17–70 cm) from the projected sea-level rise of 112 cm (49–210 cm) under a business-as-usual scenario for emissions (Representative Concentration Pathway (RCP) 6.0). The pie chart shows percentage contribution of each pollutant. Mitigation of the SLCP methane would lead to reductions in tropospheric ozone, another SLCP, and hence the pie chart includes both. As a long-lived pollutant, CO_2 plays a substantial role (blue section), but reduction in SLCPs (shown in darker colours) would lead to a larger degree of avoided sea level. (Under a more intensive business-as-usual RCP8.5 level, reductions in CO_2 would increase the share of CO_2 mitigation to 50%). (Victor D. G., *et al.* (2015) *Soot and short-lived pollutants provide political opportunity*, NATURE CLIMATE CHANGE 5:796–798, 796 (*based on* Hu A., *et al.* (2013) *Mitigation of short-lived climate pollutants slows sea-level rise*, NATURE CLIMATE CHANGE 3:730–734).)

SLCPs directly impacting the Arctic

Reducing black carbon is especially beneficial for the Arctic because black carbon not only warms the atmosphere but also facilitates additional warming. Once black carbon is deposited on the snow and ice, it reduces the reflectivity (albedo) and absorbs extra solar radiation, which leads to further melting than pristine snow and ice.[495] Since 1890, black carbon has contributed

0.5–1.4 ºC of warming to the Arctic, while tropospheric ozone—an SLCP and precursor to methane—contributed 0.2–0.4 ºC of warming.[496]

Asian nations contribute the largest portion of emissions that lead to Arctic warming, but the Arctic is most sensitive to emissions of SLCPs from Arctic nations.[497] Arctic States are responsible for 30% of black carbon's warming effects in the Arctic while only producing 10% of the emissions,[498] but shipping throughout the region is projected to increase as declining sea ice makes transportation through the region easier, which will increase the localized emissions.[499] Through the Arctic Council, the Arctic States and some Observer States "developed and submitted inventories of black carbon and methane emissions", with many submitting methane projections and some submitting black carbon projections.[500] As a result, methane emissions are projected to remain the same between 2013 and 2030 while black carbon emissions are projected to decrease by 24% from 2013 levels by 2025.[501]

OPPORTUNITIES FOR STENGTHENING SLCP MITIGATION

This section covers the existing legal and political frameworks and organizations on international, regional, national, and subnational levels. In many instances, these frameworks can be strengthened to increase reductions that will provide additional benefit to the climate. At the same time, existing legal and political strategies can provide an example to other sectors or regions where mitigation efforts can be added.

Various organizations and institutions around the world provide avenues for discussing and employing mitigation measures in different sectors. Some focus on mitigation specific emissions like through the work of the Climate and Clean Air Coalition (CCAC) with SLCPs, while others focus on a region like the Arctic Council's work with all issues involving the Arctic region, not just environmental concerns. There are also international bodies that focus on specific sectors that are working to reduce emissions and would be ideal candidates for furthering mitigation efforts.

As climate impacts to the Arctic are already occurring and will continue even with emissions reductions, Arctic communities must continually improve knowledge and assessment of the best way for the Arctic to adapt.[502] International cooperation is needed to develop long-term commitments to funding, increase understanding and application of traditional and local knowledge, and coordinate efforts with observation networks and stakeholders.[503] Additionally, raising public awareness of the implications of changes in to the snow and ice of the Arctic will help build support for fast action.[504]

Below are some selected international and national laws and policies working to reduce emissions as well as some organizations that are implementing similar strategies.

The UN Framework Convention on Climate Change (UNFCCC) and the Paris Agreement

The UN Framework Convention on Climate Change (UNFCCC) was concluded 9 May 1992 and entered into force nearly two years later, and the main objective of the treaty is the "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system."[505]

The Parties to the UNFCCC re-emphasized their commitment to stopping climate change in December 2015 with the Paris Agreement.[506] The Paris Agreement entered into force on 4 November 2016,[507] following meeting the requirements of the Agreement that at least 55 Parties to the UNFCCC that account for at least an estimated 55% of the global GHG emissions have ratified, accepted, approved, or acceded.[508] Of the 197 Parties to the UNFCCC, 180 Parties have ratified the treaty, though nearly every country signed onto the Agreement (as of August 2018), though the United States has stated its intent to withdraw from the treaty.[509]

The main goal of the Paris Agreement is to hold global temperatures to "well below 2 ºC above pre-industrial levels" and for Parties to pursue limiting the temperature increase to 1.5 ºC.[510] Parties are to peak emissions as quickly as possible—though developing countries are understood to have additional time.[511]

Fig. 17: Probable tipping points in the range of the Paris Agreement goal

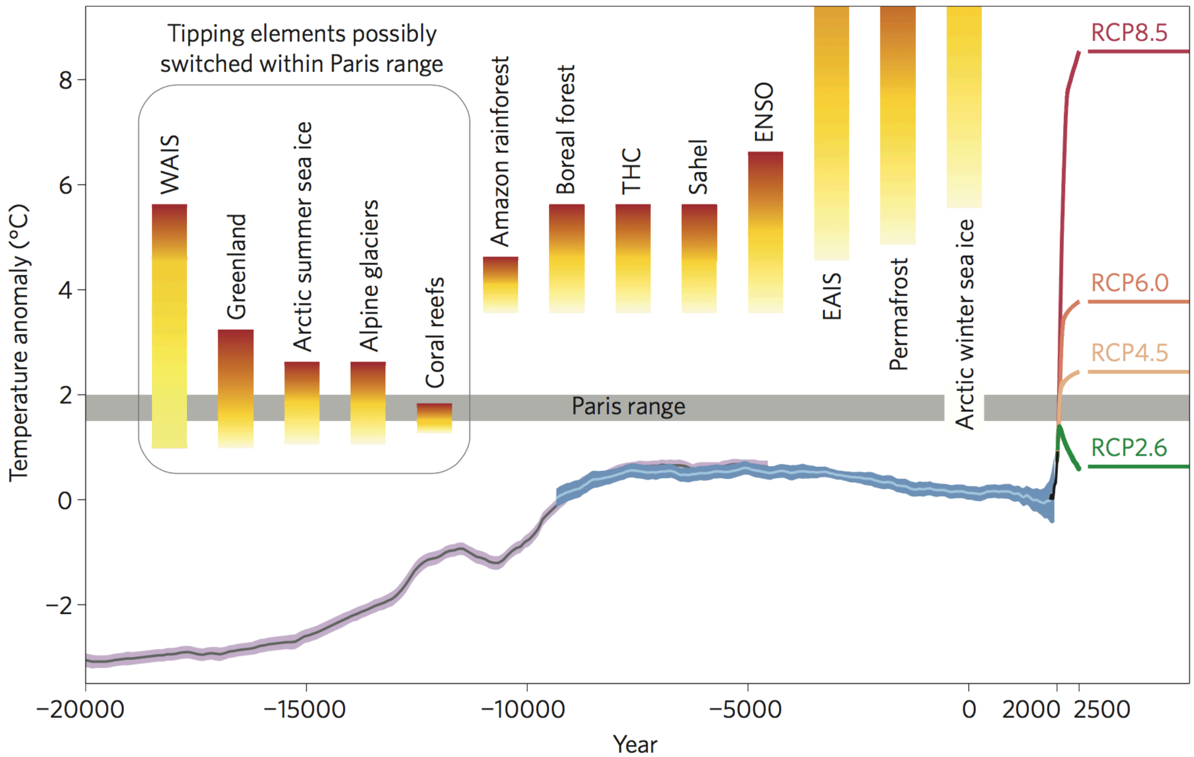


Figure 1 | Tipping elements in context of the global mean temperature evolution. Shown is the global-mean surface temperature evolution from the Last Glacial Maximum through the Holocene, based on palaeoclimatic proxy data (grey and light blue lines, with the purple and blue shading showing one standard deviation), instrumental measurements since 1750 ad (HadCRUT data, black line) and different global warming scenarios for the future…. Threshold ranges for crossing various tipping points where major subsystems of the climate system are destabilized have been added from ref. 8, 14 and 37–40. (Note that we follow the tipping point definition of Lenton et al. which does not require irreversibility, so that sea ice cover is included here.) The range for the West Antarctic Ice Sheet (WAIS) has been adapted to account for the observation that part of it has probably tipped already. THC, thermohaline circulation; ENSO, El Niño–Southern Oscillation; EAIS, East Antarctic Ice Sheet. (Schellnhuber H. J., *et al.* (2016) *Why the right climate target was agreed in Paris*, NATURE CLIMATE CHANGE 6:649–653, 650.)

Countries are to develop national mitigation measures and convey these intentions through their Nationally Determined Contributions (NDCs).[512] These pledges are to be revised every five years,[513] with each subsequent NDC reflecting increased ambition for mitigation.[514] Each Party must regularly report a national inventory of the sources and sinks of anthropogenic emissions, which is necessary to track the progress towards satisfying the pledges made in the NDCs.[515] The Paris Agreement also requires Parties to routinely check on the progress towards achieving the goals of the Agreement, referred to as the "global stocktake", and the first stocktake will occur in 2023 with subsequent ones occurring every five years.[516]

The NDCs are a critical feature of the Paris Agreement, but as they are each individually authored by the Parties, there exists significant various in what GHGs are included, how they are measured, and how the Party intends to reduce their emissions.[517] As the next round of NDCs are due by 2020, countries could opt to strengthen their overall goals for emissions reductions while also specifying attention to SLCPs.[518]

The initial mitigation targets from the NDCs are not sufficient to meet the Paris temperature goal.[519] With the current NDCs, the emissions between now and 2030 are likely to exceed the 2 ºC target.[520] In many cases, limiting warming to 1.5 ºC requires more rapid mitigation in the near-term and also increased energy efficiency.[521]

Carbon intensity of energy in the future depends upon the infrastructure put in place today, and promoting a continued decline in fossil energy requires changes to happen sooner rather than later.[522] Many of the scenarios that achieve 2ºC while also utilizing fossil energy depend on large-scale deployment of carbon capture and storage (CCS), and without such technologies, "most models cannot produce emission pathways consistent with the 2ºC goal."[523] Reality is far from matching the models because the models suggest having 4000 facilities by 2030 but only tens have been proposed by 2020.[524]

Renewables are on par with what should be happening under the 2ºC scenarios.[525] But this level of deployment of renewables is not enough. Based on the scenarios, the current NDC pledges do not cut sufficient emissions by 2030 to stay on track while at the same time CCS technologies "deviate substantially from long-term requirements to meet the Paris goal," and "there is a lack of scenarios exploring opportunities and challenges of…low CCS and high renewables."[526]

Further action is needed and must be achieve in the near-term to keep 1.5 ºC as an attainable goal, which can be achieved by countries stepping up their obligations in the near term, expanding the NDCs to include additional sectors and greenhouse gases, working within international sectors like aviation and maritime transport, and promoting additional national and subnational initiatives.[527] Achieving the Paris goals requires a dramatic shift in energy production where coal, oil, and gas are exchanged for exponentially scaled up renewable energy and energy efficiency technologies.[528] Even staying in the Paris-approved range of temperatures could lead to tipping elements being shifted into a new regime, including the possibility that the ice sheet stability in West Antarctica may have already been compromised.[529]

International action on HFCs through the Kigali Amendment to the Montreal Protocol

Hydrofluorocarbons (HFCs) are factory-made chemicals primarily used as refrigerants, foam-blowing agents, and other applications. HFCs were used to replace chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), but in many cases are no longer needed, as alternatives are available. While HFCs do not deplete the ozone layer, they are powerful greenhouse gases, the usage of which has increased 10–15% annually in recent years.[530] CFCs and HCFCs, in addition to depleting the ozone layer, are also powerful greenhouse gases, and by phasing out these chemicals, the Montreal Protocol has provided climate mitigation equivalent to 135 billion tonnes of CO_2.[531] In October 2016, the Parties to the Montreal Protocol agreed to the Kigali Amendment, which will gradually phasedown HFCs.[532] Phasing down HFCs can avoid up to 0.5 ºC of warming by 2100, and the Kigali Amendment will achieve most of that avoided warming, with the remainder possible through acceleration of the Kigali phasedown schedule.[533]

The Kigali Amendment entered into force 1 January 2019.[534] As with previous transitions under the Montreal Protocol,[535] developed countries (non-Article 5 Parties) will act first to phase down HFCs with developing countries (Article 5 Parties) following some years later.[536] Substitutes for HFCs already exist in almost every sector, which will help to speed the transition. Alternatives include fluorinated hydrofluoroolefins (HFOs), natural refrigerants, and not-in-kind alternatives.[537]

Previous transitions under the Montreal Protocol facilitated improvements in energy efficiency in the appliances that utilise these refrigerants, and similar benefits can be achieved during the transition away from high-GWP HFCs. For example, a 30% improvement in efficiency of room air conditioners avoids an additional 100 billion tonnes of CO_2-eq emissions by mid-century.[538] Furthermore, a quicker transition away from HFCs will have an added benefit of preventing the accumulation of HFCs in products and equipment that risks release of HFCs in the future when the products and equipment are disposed.[539]

SLCPs managed through the Convention on Long-Range Transboundary Air Pollution

The Convention on Long-Range Transboundary Air Pollution (LRTAP) was signed in 1979 to combat air pollution, including that which crosses international boundaries. In 1999, the Parties to the Convention agreed to the Gothenburg Protocol, which entered into force in 2005. The Gothenburg Protocol was amended in 2012 to include binding requirements to reduce fine particulate matter, specifically including black carbon in part because of the co-benefits of protecting human health and the climate—especially in the Arctic.[540]

Climate and Clean Air Coalition (CCAC)

The Climate and Clean Air Coalition (CCAC) specialises in the reductions of SLCPs, and as of June 2018 has over 120 state and non-state partners, including governments, intergovernmental organizations, and businesses.[541] The CCAC has sector specific initiatives—dealing with diesel, oil and gas, waste, brick production, HFCs, household energy, and agriculture—as well as cross-sectoral initiatives—supporting national action on SLCPs, financing projects, performing assessments, and reducing air pollution.[542] The CCAC has four key strategies: enabling transformative action, mobilising support, increasing availability of financial resources, and enhancing scientific knowledge.[543] To accomplish the CCAC's goals, they work through training, supporting development of laws and regulations, demonstrating technology, political outreach, raising awareness, co-finding and catalysing funding, and developing knowledge resources and tools.[544] The status of these projects as well as goals for future projects are contained in annual reports[545] as well as routine progress reports on individual initiatives.[546]

In September 2015, the CCAC issued the *Five-Year Strategic Plan (2020)* to build upon the success already achieved by the CCAC and focus on policies and practices to reduce SLCPs in the near- to medium-term.[547] Within the plan are four key strategies: (1) catalyse ambitious action, (2) mobilise robust support, (3) leverage finance at scale, and (4) enhance science and knowledge.[548] At the 9th High Level Assembly in November 2017, the CCAC commended the successes of the first five years and outlined a focus to reduce methane and black carbon emissions from agriculture and municipal solid waste sources for the coming year.[549]

International Maritime Organization (IMO)
The International Maritime Organization was established under the Convention on the International Maritime Organization in 1948 in Geneva, which entered into force in 1958.[550] Article 1 of the Convention establishes that the IMO is to create a vehicle for cooperation amongst countries for regulations and practices affecting shipping for international trade, including utilizing the best practicable standards for safety and controlling marine pollution.[551]

In one of its first major accomplishments, the IMO adopted the International Convention on the Safety of Life at Sea (SOLAS) in 1960.[552] An oil spill in 1967 prompted the IMO to work toward minimizing consequences, and this led to the International Convention for the Prevention of Pollution from Ships, 1973, which was modified by the Protocol in 1978; this is now known as MARPOL 73/78.[553]

In 1997, Annex VI was added to the treaty, but it did not enter into force until May 2005.[554] Annex VI covers air pollution, but as of yet, there are only standards set for sulphur oxide, nitrogen oxide, and particulate matter emissions; ozone-depleting emissions are also prohibited under Annex VI.[555] The IMO created emission control areas (ECAs) that are specific areas where these emissions are prohibited. Regulation 13 of MARPOL Annex VI applies NO_X emission controls to the following areas: Pacific coasts of the United States and Canada; the Atlantic coasts of the United States, Canada, and France; the Hawaiian Islands; and the seas of the Caribbean.[556] Regulation 14 set out the ECAs for SO_X and particulate matter emissions; these include the areas covered under Regulation 13 as well as Baltic Sea and the North Sea.[557]

Shipping in the Arctic contributes 1 to 3 per cent of global shipping emissions.[558] Overall, shipping is responsible for approximately 5% of black carbon emissions in the Arctic, but studies suggest that this could double by 2030 and quadruple by 2050.[559] Of the total emissions from shipping, CO_2 has the largest climate impact, and black carbon has the second largest climate impact.[560] CO_2 emissions from shipping were 2.6% of the global energy-related CO_2 emissions, which is up from 2.2% in 2012.[561] The IMO projects that shipping emissions could grow up to 250% by 2050.[562] Using a 20-year time scale, black carbon is equivalent to 21% of the GHG emissions from the shipping sector.[563]

The Arctic is nearly five times more sensitive to black carbon emitted in the Arctic region than from those emissions that originate in the mid-latitudes,[564] making emissions from shipping within the Arctic region critical targets for black carbon mitigation.[565] Over 2000 ships passed through the Arctic in 2015, from which 193 tonnes of black carbon were emitted; 68% of this black carbon came from burning heavy-fuel oil, even though only 42% of ships used heavy-fuel oil.[566] Broken down by country, the top three emitters of black carbon were Russia, Canada, and Denmark, which emitted 74, 8, and 7 tonnes of black carbon, respectively.[567]

There has been speculation that increased shipping will lead to increased sulphate emissions could lessen the warming in the Arctic more than the increase in warming from black carbon emissions.[568] Shipping within the Arctic could reduce Arctic warming by 1 ºC by the end of the century because sulphate-driven cloud formation cools the lower atmosphere and surface.[569] Clouds can have both a warming and cooling effect on the atmosphere, but clouds forming in the Arctic as a result of sulphate emissions are comprised of smaller droplets that scatter more incoming radiation and thus have a cooling effect, which is in addition to the general reflectivity and cooling of sulphates in the atmosphere.[570] However, cooling from increased shipping is much smaller than the anticipated Arctic warming that would allow such ice-free conditions.[571] Additionally, policies that are already in place or will be put into place to reduce sulphate emissions will lessen this aerosol cooling effect from shipping.[572]

In 2014, the IMO created the International Code for Ships Operating in Polar Waters, known as the Polar Code; the Polar Code entered into force on 1 January 2017.[573] The Polar Code achieves similar goals of other IMO-associated conventions like MARPOL but with a focus on shipping in Polar Regions.[574] Most of the Polar Code deals with overall safety requirements for ships operating in the Polar Regions, and the remainder of the Polar Code relates to pollution in the form of effluent emissions, sewage discharge, and garbage from ships.[575]

The IMO approved Regulation 43 under MARPOL, which prevents ships in the Antarctic from using or transporting heavy fuel oil,[576] and the Polar Code recommends—but does not require—that ships operating in the Arctic do the same.[577] At the February 2019 meeting of the Sub-Committee on Pollution Prevention and Response, a call was made for an assessment of the impacts of banning heavy fuel oil use within the Arctic, the results of which will be shared at the next meeting and include guidelines on appropriate measures to ban the fuel and requisite infrastructure necessary to ensure economical implementation.[578]

At the IMO's April 2018 meeting, the Marine Environment Protection Committee (MEPC) of the IMO agreed to an initial strategy[579] to address climate change whereby emissions from shipping should peak as soon as possible and total greenhouse gas emissions should be reduced by at least 50% by 2050 compared to 2008 levels.[580] The IMO has previously instituted rules on improving energy efficiency in shipping through better engines and equipment,[581] and some countries have proposed strengthening the 2011 IMO regulations on energy-efficiency, requiring the use of cleaner fuels and newer engines, or purchasing carbon-offset credits.[582] The IMO currently has regulations in place to minimize emissions of sulphur oxides (SO_X) and nitrogen oxides (NO_X), which could be expanded to include other air and climate pollutants like black carbon.[583] The Sub-Committee on Pollution Prevention and Response identified potential measures to reduce black carbon emissions in the Arctic, forwarding them to the Marine Environment Protection Committee for discussion during their May 2019 meeting.[584]

Individual shipping companies can also contribute to efforts. In December 2018, Maersk, the world's largest shipping company, announced its intentions to cut net carbon emissions to zero by 2050, which is the most ambitious goal of the shipping industry and a move that will require carbon-free ships by 2030.[585]

International Civil Aviation Organization (ICAO)

The International Civil Aviation Organization (ICAO) is a specialized agency of the UN that manages implementation of the Convention on International Civil Aviation, also known as the Chicago Convention,[586] and the ICAO came into existence when the Chicago Convention entered into force on 4 April 1947.[587] The ICAO is comprised of the Assembly of representations from all member States; the Council of 36 States elected by the Assembly and holding the position for three years; and the Secretariat.[588] The ICAO works alongside other international organizations, including the World Meteorological Organization, the World Health Organization, and the International Maritime Organization;[589] the ICAO also works with assorted non-governmental organizations.[590]

The ICAO produces annual reports that are available online and dissected into individual topic areas and discussions.[591] Within the ICAO, the Committee on Aviation Environmental Protection (CAEP) addresses environmental concerns, assisting the Council in developing standards and practices related to noise and emissions.[592] In October 2016, the ICAO approved Resolution 22/2 that included a plan for members of the ICAO to take steps to reduce CO_2 emissions in aviation as part of its Global Market-Based Measure scheme.[593] In September 2017, the ICAO developed draft rules relating to CO_2 emissions, and two months later, the CAEP presented proposal for a fourth volume of the *Environmental Technical Manual* and other implementation guidance.[594] By the end of 2017, 72 States had volunteered to participate in the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) initiative.[595]

Arctic Council

The Arctic Council was established under the Ottawa Declaration as a proclamation of Canada, Denmark, Finland, Iceland, Norway, Russia, Sweden, and the United States to work together to safeguard the Arctic and promote sustainable development within it.[596] These countries all border the Arctic and have a vested interest in cooperating within the region. There are also observer states[597] and organizations[598] that can contribute to the work of the Arctic Council, primarily through contributions to Working Groups.[599]

In the over two decades since its inception, the Arctic Council has developed Working Groups that provide a forum for discussions and negotiations pertaining to the Arctic.[600] While the Arctic Council can develop recommendations and guidelines, the lack of an enforcement entity forces each Arctic state to be individually responsible.[601]

Through the Arctic Council, the Arctic States and some Observer States "developed and submitted inventories of black carbon and methane emissions".[602] Both shipping and flaring from oil and gas industries are projected to increase in the Arctic, contributing to emissions of SLCPs.[603] With declining sea ice, more trade routes through the Arctic are projected to open, and global shipping is likely to increase, resulting in a doubling of emissions.[604]

The Arctic Council noted that emissions from shipping could be reduced through international action under the International Maritime Organization (IMO); an agreement under the IMO limits sulphur oxide and nitrogen oxide emissions while also engaging in policies aimed at implementing abatement technologies.[605] As a result of these actions, black carbon emissions are projected to decrease by 24% from 2013 levels by 2025.[606]

The Arctic Contaminants Action Program (ACAP) is one of the permanent Working Group of the Arctic Council and serves to encourage countries to reduce emissions and pollutants.[607] The ACAP is one of the four expert groups of the Arctic Council that specializes in SLCPs.[608]

National and subnational laws regarding SLCP mitigation

An international agreement tailored specifically to SLCPs has not been engineered. However, some countries and even collectives of countries have begun taking steps to establish laws and regulations that will mitigate SLCPs.

On 17 July 2017, the European Union accepted an amendment to the Gothenburg Protocol (a protocol to the Convention on Long-range Transboundary Air Pollution, discussed below) that included particulate matter, noting that the E.U. had already implemented various Directives and Regulations that would be required under the Gothenburg Protocol.[609] For example, Directive 2016/2284 requires ozone and particulate matter, among other air pollutants, to be regulated by E.U. Members and notes that countries should prioritise black carbon emissions as part of their initiatives to reduce particulate matter.[610]

Policies in Sweden and The Netherlands represent examples of actions that have been taken by E.U. members. Sweden places both an energy tax and a carbon dioxide tax on diesel fuel, and both taxes will increase by 2% each year starting in 2017.[611] The Netherlands has reduced emissions of black carbon by introducing E.U. emission standards, including diesel particulate filters.[612] The Netherlands has also reduced emissions of methane through better waste management practices and improvements within the oil, gas, and aluminium industries.[613] Further, The Netherlands established The Netherlands Polar Programme as part of the overall Dutch Polar Strategy 2016–2020. The purpose of this program is to focus on the priority issues of ice, climate and sea-level rise, and others.[614]

While the U.S. as a whole has not addressed SLCPs through federal legislation, California has enacted two laws relating to SLCPs. In 2006, California passed AB32, requiring California to reduce greenhouse gas emissions—including methane and HFCs—to 1990 levels by 2020, which is about 15% below what was expected under business-as-usual practices.[615] In 2016, California passed a bill specific to SLCPs that would require the California Air Resources Board (CARB) to monitor and regulate emissions such that there is a reduction in methane by 40%, HFCs by 40%, and black carbon by 50% below 2013 levels by 2030,[616] and in September 2018, California passed legislation that would phasedown HFCs.[617]

The Under2 Coalition began in May 2015 with 12 founding members and has since grown to include over 200 nations, states, regions, provinces, and cities.[618] The overall goal of the members is to limit their greenhouse gas emissions by 80–95% below 1990 levels by 2050.[619]

U.S. Climate Alliance

The U.S. Climate Alliance is a bipartisan coalition that focuses on states taking the lead on climate change, noting that state-level action benefits state economies all while demonstrating the achievability of aggressive climate action.[620] Participants with the U.S. Climate Alliance commit themselves to implementing policies in line with the goals of the Paris Agreement to reduce GHG emissions by at least 26–28 per cent below 2005 levels by 2025, which includes tracking and reporting progress as well as accelerating new and existing policies on clean energy.[621]

In June 2018, the U.S. Climate Alliance announced a commitment to reducing SLCPs because of the near-term climate benefits and the co-benefits to health, agriculture, and ecosystems.[622] With this pledge, the U.S. Climate Alliance seeks to encourage national and subnational jurisdictions and businesses to commit to reducing SLCPs through improvements to emissions inventories, identification of methane leaks, promotion of energy efficiency (including refrigeration and cooling), phasedown of HFCs, and improvements in agricultural management and waste.[623]

Intersection of SLCP mitigation with Sustainable Development Goals (SDGs)

Many measures to reduce SLCPs will help countries address the Sustainable Development Goals (SDGs)[624] and their targets with minimal trade-offs and conflicts; this is in addition to co-benefits of SLCP and CO_2 mitigation.[625]

Methane measures involve degasification and recover of coal mines, recovery and utilization of fugitive emissions in oil and gas production, reducing leakage in natural gas transmission, addressing methane from municipal waste and landfills, better treatment of wastewater, promoting anaerobic digestion in livestock, and intermittent aeration for rice paddies.[626] The associated SDGs include food security and hunger (Goal 2), promoting health through reducing air pollution (Goal 3), strengthening energy reliability (Goal 7) while promoting economic growth (Goal 8) through better infrastructure (Goal 9), and resulting in more sustainable production and consumption (Goal 12); all of this is in addition to climate protection (Goal 13).[627]

Black carbon measures include improving standards and particulate filters for diesel vehicles, eliminating high-emitting diesel vehicles, replacing traditional cookstoves with clean-burning stoves, replacing brick kilns with more efficient technologies, banning open burning of agricultural waste, replacing kerosene wick lamps with clean lighting, eliminating gas flaring, promoting walking and biking as means of travel, and encouraging healthy diets with less meat.[628] The SDGs met through these measures include health (Goal 3), hunger (Goal 2), poverty (Goal 1), sustainable cities and communities (Goal 11), education (Goal 4), gender equality (Goal 5), energy (Goal 7), infrastructure (Goal 9), economic growth (Goal 8), and overall climate benefits (Goal 13).[629]

For measures related to HFCs, the combination of replacing high-GWP HFCs with low-impact alternatives alongside a transition to super-efficient appliances will address the SDGs to reduce poverty (Goal 1), provide energy (Goal 7), economic development (Goal 8), sustainable cities and communities (Goal 11), and sustainable production and consumption (Goal 12).[630]

CONCLUSION

Recent changes in the Arctic are harbingers of what is to the come to the region, and climate-warming impacts in Antarctica are increasingly causing concerns amongst scientists of committed significant sea level rise. As temperatures continue to rise, the Polar Regions are facing an increasingly dire situation. Staving off the most devastating effects demands swift action to reduce the rate of warming and to secure long-term climate stability.

The Arctic is warming twice as fast as the rest of the world, a trend that will continue as global temperatures rise. Repercussions of this amplified warming are already being witnessed through decreasing Arctic sea ice extent and accelerated melting of the Greenland ice sheet and could soon thaw permafrost that would unleash an immense feedback on the climate system.

We must act with upmost speed to stay under 2 ºC, and even more so to achieve 1.5 ºC, because some tipping points and feedbacks are instigated prior to 2 ºC and other impacts of climate change are exacerbated as temperatures warm from 1.5 ºC to 2 ºC. Slowing warming globally and in the Arctic is essential to avoid a cascade of feedbacks that would push the global climate into a new and unknown climate regime.

Existing laws and regulations can serve as guides for others looking to develop and expand their own initiatives to reduce emissions of greenhouse gases. Successful initiatives can inspire other countries to take similar steps. For institutions that have yet to achieve success at the necessary level to maintain a stable climate, existing pieces of legislation can provide models for action, making it easier to embrace the challenges and achieve success.

Appendix I: List of acronyms and abbreviations

ºC	degrees Celsius
ACAP	Arctic Contaminants Action Program
AMAP	Arctic Monitoring & Assessment Programme
A5 Parties	developing countries qualified for grace periods and MFL financing under the Montreal Protocol
AR5	Fifth Assessment Report of the IPCC
BAU	business-as-usual
BC	black carbon
C	carbon
CARB	California Air Resources Board
CFC	chlorofluorocarbon
CH_4	methane
CO_2	carbon dioxide
CO_2-eq	carbon dioxide equivalent
EAIS	East Antarctic Ice Sheet
ENSO	El Niño-Southern Oscillation
E.U.	European Union
GHG	greenhouse gas
GrIS	Greenland Ice Sheet
Gt	gigatonne (billion tonnes)
GWP	global warming potential
HCFCs	hydrochlorofluorocarbon
HFCs	hydrofluorocarbon
HFOs	hydrofluoroolefins
HFO	heavy fuel oil
ICAO	International Civil Aviation Organization
IEA	International Energy Agency
IGSD	Institute for Governance & Sustainable Development
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
MEPC	Marine Environment Protection Committee
NASA	National Aeronautics & Space Administration
NASA GISS	National Aeronautics & Space Administration Goddard Institute for Space Studies
NGO	non-governmental organization
NOAA	National Oceanic & Atmospheric Administration
Non-A5 Parties	developed countries to the Montreal Protocol
NO_X	nitrogen oxides
NSIDC	National Snow & Ice Data Center
ODS	ozone-depleting substance
PETM	Palaeocene-Eocene Thermal Maximum
Pg	petagram (equal to billion tonnes)
RCP	Representative Concentration Pathway
SDG	Sustainable Development Goal
SLCP	short-lived climate pollutant
SLR	sea-level rise
SO_X	sulphur oxides
U.K.	United Kingdom
UN	United Nations
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
U.S.	United States
U.S. EPA	United States Environmental Protection Agency
WAIS	West Antarctic Ice Sheet
WHO	World Health Organization
WMO	World Meteorological Organization

ENDNOTES

[1] Arctic Monitoring and Assessment Programme (AMAP) (2017) SNOW, WATER, ICE, AND PERMAFROST IN THE ARCTIC: SUMMARY FOR POLICYMAKERS, 8 ("The Arctic is still a cold place, but it is warming faster than any other region on Earth. Over the past 50 years, the Arctic's temperature has risen by more than twice the global average. Increasing concentrations of greenhouse gases in the atmosphere are the primary underlying cause: the heat trapped by greenhouse gases triggers a cascade of feedbacks that collectively amplify Arctic warming.").

[2] A tipping element is a component of the Earth climate system that is sufficiently large in scale and capable of existing in two or more qualitatively different states. These states can be altered by some small perturbation—the tipping point—that ialters the future of the tipping element. The transition to the future state can occur quickly or take many decades, centuries, or even millennia to appear. *See* Lenton T., *et al.* (2008) *Tipping elements in the Earth's climate system*, PROC. NAT'L. ACAD. SCI. 105(6):1786–1793, 1786 ("In discussions of global change, the term tipping point has been used to describe a variety of phenomena, including the appearance of a positive feedback, reversible phase transitions, phase transitions with hysteresis effects, and bifurcations where the transition is smooth but the future path of the system depends on the noise at a critical point. We offer a formal definition, introducing the term ''tipping element'' to describe subsystems of the Earth system that are at least subcontinental in scale and can be switched—under certain circumstances— into a qualitatively different state by small perturbations. The tipping point is the corresponding critical point—in forcing and a feature of the system—at which the future state of the system is qualitatively altered."); Lenton T. (2011) *Early warning of climate tipping points*, NATURE CLIMATE CHANGE 1:201–209, 202 ("The phrase 'tipping point' captures the colloquial notion that 'little things can make a big difference', that is, at a particular moment in time, a small change can have large, long-term consequences for a system. The term 'tipping element' was introduced to describe large-scale subsystems (or components) of the Earth system that can be switched — under certain circumstances — into a qualitatively different state by small perturbations. These must be at least sub-continental in scale (length scale of order ~1,000 km). The tipping point is the corresponding critical point — in forcing and a feature of the system — at which the future state of the system is qualitatively altered. …In this definition, the critical threshold (ρ_{crit}) is the tipping point, beyond which a qualitative change occurs, and the change may occur immediately after the cause or much later."); *and* Kopp R. E., *et al.* (2016) *Tipping elements and climate–economic shocks: Pathways toward integrated assessment*, EARTH'S FUTURE 4:346–372, 347 ("*Lenton et al*. [2008] formalized the concept of "tipping points" in the climate system in a way that loosened this definition. *Lenton et al*. [2008] defined a "tipping element" as a subsystem of the Earth system, subcontinental or larger, that small perturbations can shift into multiple different stable states. A tipping element's tipping point is a critical threshold at which "a small change in forcing triggers a strongly nonlinear response in the internal dynamics of part of the climate system, qualitatively changing its future state" [*Lenton*, 2011, p. 201]. *Lenton* [2013] noted that the triggering forcing might arise as a result of the level of forcing, the rate of forcing, or system noise.").

[3] Steffen W., *et al.* (2018) *Trajectories of the Earth System in the Anthropocene*, PROC. NAT'L. ACAD. SCI. 115(33):8252–8259, 8254 ("This risk is represented in Figs. 1 and 2 by a planetary threshold (horizontal broken line in Fig. 1 on the Hothouse Earth pathway around 2 °C above preindustrial temperature). Beyond this threshold, intrinsic biogeophysical feedbacks in the Earth System (Biogeophysical Feedbacks) could become the dominant processes controlling the system's trajectory. Precisely where a potential planetary threshold might be is uncertain (15, 16). We suggest 2 °C because of the risk that a 2 °C warming could activate important tipping elements (12, 17), raising the temperature further to activate other tipping elements in a domino-like cascade that could take the Earth System to even higher temperatures (Tipping Cascades). Such cascades comprise, in essence, the dynamical process that leads to thresholds in complex systems (section 4.2 in ref. 18).").

[4] Steffen W., *et al.* (2018) *Trajectories of the Earth System in the Anthropocene*, PROC. NAT'L. ACAD. SCI. 115(33):8252–8259, 8255, Figure 3.

[5] Norris J. R., *et al.* (2016) *Evidence for climate change in the satellite cloud record*, NATURE 536:72–75, 72 ("Here we show that several independent, empirically corrected satellite records exhibit large-scale patterns of cloud change between the 1980s and the 2000s that are similar to those produced by model simulations of climate with recent historical external radiative forcing. Observed and simulated cloud change patterns are consistent with poleward retreat of mid-latitude storm tracks, expansion of subtropical dry zones, and increasing height of the highest cloud tops at all latitudes. The primary drivers of these cloud changes appear to be increasing greenhouse gas concentrations and a recovery from volcanic radiative cooling. These results indicate that the cloud changes most consistently predicted by global climate models are currently occurring in nature."); *see also* Bender F. A.-M., *et al.* (2012) *Changes in extratropical storm track cloudiness 1983–2008: observational support for a poleward shift*,

CLIMATE DYNAMICS 38(9–10):2037–2053, 2037 ("Climate model simulations suggest that the extratropical storm tracks will shift poleward as a consequence of global warming. In this study the northern and southern hemisphere storm tracks over the Pacific and Atlantic ocean basins are studied using observational data, primarily from the International Satellite Cloud Climatology Project, ISCCP. … It is found that the storm tracks, here represented by the extent of the mid-latitude-centered band of maximum cloud cover over the studied ocean basins, experience a poleward shift as well as a narrowing over the 25 year period covered by ISCCP. … The observed changes in storm track cloudiness can be related to local cloud-induced changes in radiative forcing, using ERBE and CERES radiative fluxes. The shortwave and the longwave components are found to act together, leading to a positive (warming) net radiative effect in response to the cloud changes in the storm track regions, indicative of positive cloud feedback. Among the CMIP3 models that simulate poleward shifts in all four storm track areas, all but one show decreasing cloud amount on a global mean scale in response to increased CO_2 forcing, further consistent with positive cloud feedback. Models with low equilibrium climate sensitivity to a lesser extent than higher-sensitivity models simulate a poleward shift of the storm tracks."); *and* Committee to Prevent Extreme Climate Change (2017) *Well Under 2 Degrees Celsius: Fast Action Policies to Protect People and the Planet from Extreme Climate Change*, 9 ("Though clouds enhance the greenhouse effect by trapping heat, they also reflect an enormous amount of solar radiation and nearly double the albedo of the planet. Their albedo effect dominates over their greenhouse effect, balancing out to a net cooling of about $-25\ Wm^{-2}$ (compared with the $1.6\ Wm^{-2}$ forcing from CO_2 and total current forcing of $3\ Wm^{-2}$) (IPCC, 2013). More than two-thirds of this cooling is from the extensive extratropical cloud systems, which are found poleward of about 40° and are associated with jet streams and storm tracks (IPCC, 2013). Satellite data reveal that these cloud systems are retreating poleward in both hemispheres, which has led to an increase in the solar radiation reaching the extratropics, further amplifying warming (Bender et al., 2012; Norris et al., 2016). Thus, the Arctic warming is amplified by two large feedbacks: first is the decrease in albedo from the retreating sea ice, which is then further amplified by the decrease in albedo from the shrinking storm track clouds.").

[6] National Snow & Ice Data Center (NSIDC), *All about the Cryosphere* (*last accessed* 4 May 2018) ("Some places on Earth are so cold that water is a solid—ice or snow. Scientists call these frozen places of our planet the 'cryosphere.' The word 'cryosphere' comes from the Greek word for cold, 'kryos.' The cold regions of our planet influence our entire world's climate. Plus, the cryosphere is central to the daily lives of the people, plants, and animals that have made it their home. When scientists talk about the cryosphere, they mean the places where water is in its solid form, where low temperatures freeze water and turn it into ice. People most often think of the cryosphere as being at the top and bottom of our planet, in the polar regions. We call the area around the North Pole the Arctic and the area around the South Pole the Antarctic. But snow and ice are also found at many other locations on Earth.").

[7] National Snow & Ice Data Center (NSIDC), *All about the Cryosphere* (*last accessed* 4 May 2018) ("The North Pole is covered by a cold ocean called the Arctic Ocean. In the Arctic Ocean, sea ice grows in the winter and shrinks in the summer. Frozen ground and permafrost ring the Arctic Ocean. Glaciers, snow, and ice cover the nearby land, including a thick sheet of snow and ice covering Greenland.").

[8] National Snow & Ice Data Center (NSIDC), *All about the Cryosphere* (*last accessed* 4 May 2018) ("Antarctica, at Earth's South Pole, is an icy continent. A huge ice sheet covers the land mass of Antarctica and, in some places, shelves of floating ice extend into the ocean. The outer sections of ice break off or "calve" from these shelves and form icebergs. The icebergs float in the oceans, melting and falling apart as they drift into warmer waters.").

[9] Arctic Monitoring and Assessment Programme (AMAP) (2017) SNOW, WATER, ICE, AND PERMAFROST IN THE ARCTIC: SUMMARY FOR POLICYMAKERS, 8 ("Since 2011, evidence for the Arctic's evolution toward a new state has grown stronger. Additional years of data show continued or accelerating trends in record warm temperatures, changes in sea ice and snow, melting of glaciers and ice sheets, freshening and warming of the Arctic Ocean, thawing of permafrost, and widespread ecological changes.").

[10] The term "short-lived climate pollutants" (SLCPs)—or short-lived super pollutants—will be used through this Primer, but note that some publications use the term "short-term climate forcers" (SLCFs). SLCPs are so named because of their short atmospheric lifetimes: days to weeks for black carbon, a little over a decade for methane, and roughly fifteen years for some HFCs. Removing SLCPs leads to relatively immediate benefits that, when coupled with CO_2 mitigation, can have lasting impacts on the climate. *See* Shoemaker J. K., *et al.* (2013) *What Role for Short-Lived Climate Pollutants in Mitigation Policy?*, SCIENCE 342:1323–1324, 1323–1324 ("Direct comparisons of the climate influence of SLCPs and CO_2 require making a judgment about the relative importance of short and long time scales. SLCPs have a powerful impact on climate, but they persist in the atmosphere for only a short time—days to weeks for BC, a decade for CH_4, and about 15 years for some HFCs. Thus, immediate reductions in SLCPs will result in relatively immediate climate benefits, as the effects on climate depend largely on the emission rate, or

flow, of SLCPs to the atmosphere. …It is also important to recognize that CO_2 and SLCP emissions are not independent. Some of the steps to reduce CO_2 emissions will drive down emissions of SLCPs, as some of the largest sources of BC and methane are associated with fossil fuel production and combustion.").

[11] Lenton T. M. (2012) *Arctic Climate Tipping Points*, AMBIO, 41:10–22, 19 ("This mixture of forcing agents opens up avenues for mitigation policy (Lenton 2011a; Lenton 2011b). CO_2 is an extremely long-lived gas, so we can only change its concentration gradually by limiting our CO_2 emissions, and we must act globally. Methane has a shorter lifetime of around a decade, offering a more rapid response of its concentration to reducing emissions. Tropospheric ozone and black carbon have much shorter lifetimes still, such that a reduction in production translates almost instantaneously into a reduction in radiative forcing. Furthermore, particular regions of the world make a disproportionate contribution to Arctic radiative forcing from these agents. Consequently, efforts to restrict black carbon emissions through e.g. national air pollution policies and appropriate technologies, in e.g. China and India, could be a quick way to start limiting Arctic radiative forcing. The incentives (financial or otherwise) needed to help such countries protect the Arctic in this way, merit consideration. Of course CO_2 must also be globally tackled, and we should start reducing CO_2 emissions now to reduce the risk of more distant Arctic tipping points."); *see also* Duarte C. M., *et al.* (2012) *Abrupt climate change in the Arctic*, NATURE CLIMATE CHANGE 2:60–62, 62 ("Methane and the tropospheric ozone produced from it are also significant contributors to Arctic warming. Encouragingly, around 40% of global anthropogenic methane emissions could be mitigated at zero cost or with net economic benefit (the stumbling block being that the benefits are shared by everyone, whereas the mitigation costs are borne by only a few). Of course in the long term, restricting cumulative emissions of carbon dioxide is essential for safeguarding slow tipping elements such as the Greenland ice sheet.").

[12] *See generally* UNEP & WMO (2011) INTEGRATED ASSESSMENT OF BLACK CARBON AND TROPOSPHERIC OZONE; Shindell D., *et al.* (2012) *Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security*, SCIENCE 335(6065):183–189; Arctic Council Secretariat (2017) EXPERT GROUP ON BLACK CARBON AND METHANE: SUMMARY OF PROGRESS AND RECOMMENDATIONS 2017.

[13] UNEP (2016) REPORT OF THE TWENTY-EIGHTH MEETING OF THE PARTIES TO THE MONTREAL PROTOCOL ON SUBSTANCES THAT DEPLETE THE OZONE LAYER, UNEP/OzL.Pro.28/12, Decision XXVIII/1: Further Amendment to the Montreal Protocol; *see also* Molina M., *et al.* (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 ("We define ''fast-action'' to include regulatory measures that can begin within 2–3 years, be substantially implemented in 5–10 years, and produce a climate response within decades. We discuss strategies for short-lived non-CO_2 GHGs and particles, where existing agreements can be used to accomplish mitigation objectives. Policy makers can amend the Montreal Protocol to phase down the production and consumption of hydrofluorocarbons (HFCs) with high global warming potential. Other fast-action strategies can reduce emissions of black carbon particles and precursor gases that lead to ozone formation in the lower atmosphere, and increase biosequestration, including through biochar. These and other fast-action strategies may reduce the risk of abrupt climate change in the next few decades by complementing cuts in CO_2 emissions."); *and* Wallack J. S. & Ramanathan V. (2009) *The Other Climate Changers Why Black Carbon and Ozone Also Matter*, FOREIGN AFFAIRS 88(5):105–113, 113 ("At the current rate of global warming the earth's temperature stands to careen out of control. Now is the time to look carefully at all the possible brakes that can be applied to slow climate change, hedge against near-term climate disasters, and buy time for technological innovations. Of the available strategies, focusing on reducing emissions of black carbon and ozone precursors is the low-hanging fruit: the costs are relatively low, the implementation is feasible, and the benefits would be numerous and immediate.").

[14] World Meteorological Organization (WMO) (2018) WMO STATEMENT ON THE STATE OF THE GLOBAL CLIMATE IN 2017, 4 ("Global mean temperatures in 2017 were 1.1 °C ± 0.1 °C above pre-industrial levels. Whilst 2017 was a cooler year than the record-setting 2016, it was still one of the three warmest years on record, and the warmest not in uenced by an El Niño event. The average global temperature for 2013–2017 is close to 1 °C above that for 1850–1900 and is also the highest five-year average on record.").

[15] Allen M., *et al.* (2018) SUMMARY FOR POLICYMAKERS, *in* IPCC (2018) GLOBAL WARMING OF 1.5 ºC, 6 ("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*)").

[16] Xu Y., *et al.* (2018) *Global warming will happen faster than we think*, NATURE, Comment, 564:30–32, 30–31 ("But the latest IPCC special report underplays another alarming fact: global warming is accelerating. Three trends—rising emissions, declining air pollution and natural climate cycles—will combine over the next 20 years to make climate change faster and more furious than anticipated.").

[17] National Oceanic and Atmospheric Administration (NOAA), *Global Climate Report - Annual 2018* (*last accessed* 21 March 2019) ("During the 21st century, the global land and ocean temperature departure from average has reached new record highs five times (2005, 2010, 2014, 2015, and 2016), with three of those being set back-to-back. From 1880 to 1980, a new temperature record was set on average every 13 years; however, for the period 1981–2018, the frequency of a new record has increased on average to once every three years. Nine of the 10 warmest years (listed below) have occurred since 2005, with the last five years (2014–2018) ranking as the five warmest years on record. The year 1998 is the only year from the 20th century among the ten warmest years on record, currently tying with 2009 as the ninth warmest year on record. The yearly global land and ocean temperature has increased at an average rate of 0.07°C (0.13°F) per decade since 1880; however, the average rate of increase since 1981 (0.17°C / 0.31°F) is more than twice as great."). Rate of warming is best calculated for a large swath of years as to rule out decadal and interannual variability. As an example, the IPCC notes that warming from 1998 to 2012 yields a rate of 0.05ºC per decade whereas the longer timescale of 1951 to 2012 results in a warming of 0.12 ºC per decade, which is more representative of the long-term trend and not as easily affected by something like El Niño that increase the global average temperature for a year (like in 1998 or in 2016). Alexander L. V., *et al.* (2013) SUMMARY FOR POLICYMAKERS, *in* IPCC (2013) CLIMATE CHANGE 2013: THE PHYSICAL SCIENCE BASIS, Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 5 ("In addition to robust multi-decadal warming, global mean surface temperature exhibits substantial decadal and interannual variability (see Figure SPM.1). Due to natural variability, trends based on short records are very sensitive to the beginning and end dates and do not in general reflect long-term climate trends. As one example, the rate of warming over the past 15 years (1998–2012; 0.05 [–0.05 to 0.15] ºC per decade), which begins with a strong El Niño, is smaller than the rate calculated since 1951 (1951–2012; 0.12 [0.08 to 0.14] ºC per decade).").

[18] Smith S. J., *et al.* (2015) *Near-term acceleration in the rate of temperature change*, NATURE CLIMATE CHANGE 5:333–336, 333 ("The rate of climate change over multi-decadal scales is also important, with faster rates of change resulting in less time for human and natural systems to adapt. We find that present trends in greenhouse-gas and aerosol emissions are now moving the Earth system into a regime in terms of multi-decadal rates of change that are unprecedented for at least the past 1,000 years. The rate of global-mean temperature increase in the CMIP5 (ref. 3) archive over 40-year periods increases to 0.25 ± 0.05 ºC (1σ) per decade by 2020, an average greater than peak rates of change during the previous one to two millennia. Regional rates of change in Europe, North America and the Arctic are higher than the global average. Research on the impacts of such near-term rates of change is urgently needed.").

[19] World Meteorological Organization (WMO) (2018) WMO STATEMENT ON THE STATE OF THE GLOBAL CLIMATE IN 2017, 4 ("The overall risk of heat-related illness or death has climbed steadily since 1980, with around 30% of the world's population now living in climatic conditions that deliver deadly temperatures at least 20 days a year.").

[20] Mantyka-Pringle C. S., *et al.* (2012) *Interactions between climate and habitat loss effects on biodiversity: a systematic review and meta-analysis*, GLOBAL CHANGE BIOLOGY 18:1239–1252, 1240 ("For landscapes undergoing climate change, the effects are less clear. In terms of potential risks to biodiversity, species responses to climate change vary considerably, depending on which species are studied, whether there are any interactions between drivers, whether there are any species interactions, and the spatial and temporal scale considered (de Chazal & Rounsevell, 2009). On a global scale, many species have been or are expected to shift their ranges to higher latitudes: from the tropics to the poles (Hickling et al., 2005, 2006; Wilson et al., 2005). Others will retract and potentially face extinction (Pounds et al., 2006; Thomas et al., 2006; Sekercioglu et al., 2008). The evidence for these changes, however, comes mostly from the documented shifts in the distributions of a few well-studied taxonomic groups (e.g. birds, butterflies and vascular plants) (e.g. Hickling et al., 2005, 2006; Sekercioglu et al., 2008)."); *see also* Pecl G. T., *et al.* (2017) *Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being*, SCIENCE 335(eaai9214):1–9, 1 ("Marine, freshwater, and terrestrial organisms are altering distributions to stay within their preferred environmental conditions (5–8), and species are likely changing distributions more rapidly than they have in the past (9). Unlike the introduction of non-native species, which tends to be idiosyncratic and usually depends on human-mediated transport, climate-driven redistribution is ubiquitous, follows repeated patterns, and is poised to influence a greater proportion of Earth's biota.").

[21] Descamps S., *et al.* (2017) *Climate change impacts on wildlife in a High Arctic archipelago – Svalbard, Norway*, GLOBAL CHANGE BIOLOGY 23:490–502, 490 ("In the terrestrial ecosystem, increased winter air temperatures and concomitant increases in the frequency of 'rain-on-snow' events are one of the most important facets of climate change with respect to impacts on flora and fauna. Winter rain creates ice that blocks access to food for herbivores and synchronizes the population dynamics of the herbivore–predator guild. In the marine ecosystem, increases in sea temperature and reductions in sea ice are influencing the entire food web. These changes are affecting the foraging

and breeding ecology of most marine birds and mammals and are associated with an increase in abundance of several temperate fish, seabird and marine mammal species. Our review indicates that even though a few species are benefiting from a warming climate, most Arctic endemic species in Svalbard are experiencing negative consequences induced by the warming environment."); *see also* Pecl G. T., *et al.* (2017) *Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being*, SCIENCE 335(eaai9214):1–9, 3 ("Indirect effects from changes in species distributions that underpin society and culture can be dramatic. In the Arctic, changes in distributions of fish, wild reindeer, and caribou are affecting the food security, traditional knowledge systems, and endemic cosmologies of indigenous societies (Figs. 1 and 2) (7).").

[22] Bindoff N. L., *et al.* (2013) CHAPTER 10: DETECTION AND ATTRIBUTION OF CLIMATE CHANGE: FROM GLOBAL TO REGIONAL, *in* IPCC (2013) CLIMATE CHANGE 2013: THE PHYSICAL SCIENCE BASIS, Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 906 ("Of principal importance is 'Arctic Amplification' (see Box 5.1) where surface temperatures in the Arctic are increasing faster than elsewhere in the world."); *see also* Francis J. A. & Vavrus S. J. (2015) *Evidence for a wavier jet stream in response to rapid Arctic warming*, ENVTL. RESEARCH LETTERS 10(014005):1–12, 1 ("This paper builds on the proposed linkage between Arctic amplification (AA)—defined here as the enhanced sensitivity of Arctic temperature change relative to mid-latitude regions—and changes in the large-scale, upper-level flow in mid-latitudes. Widespread Arctic change continues to intensify, as evidenced by continued loss of Arctic sea ice; decreasing mass of Greenland's ice sheet, rapid decline of snow cover on Northern hemisphere continents during early summer, and the continued rapid warming of the Arctic relative to mid-latitudes. While these events are driven by AA, they also amplify it: melting ice and snow expose the dark surfaces beneath, which reduces the surface albedo, further enhances the absorption of insolation, and exacerbates melting. Expanding ice-free areas in the Arctic Ocean also lead to additional evaporation that augments warming and Arctic precipitation.").

[23] Arctic Monitoring and Assessment Programme (AMAP) (2017) SNOW, WATER, ICE, AND PERMAFROST IN THE ARCTIC: SUMMARY FOR POLICYMAKERS, 8 ("The Arctic is still a cold place, but it is warming faster than any other region on Earth. Over the past 50 years, the Arctic's temperature has risen by more than twice the global average. Increasing concentrations of greenhouse gases in the atmosphere are the primary underlying cause: the heat trapped by greenhouse gases triggers a cascade of feedbacks that collectively amplify Arctic warming.").

[24] National Oceanic and Atmospheric Administration (NOAA) *Global Climate Report – Annual 2018* (*last accessed* 14 February 2019) ("The yearly global land and ocean temperature has increased at an average rate of 0.07°C (0.13°F) per decade since 1880; however, the average rate of increase since 1981 (0.17°C / 0.31°F) is more than twice as great.").

[25] National Oceanic and Atmospheric Administration (NOAA) *Global Climate Report – Annual 2018* (*last accessed* 14 February 2019) ("2018 also marks the 42nd consecutive year (since 1977) with global land and ocean temperatures, at least nominally, above the 20th century average. During the 21st century, the global land and ocean temperature departure from average has reached new record highs five times (2005, 2010, 2014, 2015, and 2016), with three of those being set back-to-back. From 1880 to 1980, a new temperature record was set on average every 13 years; however, for the period 1981–2018, the frequency of a new record has increased on average to once every three years.").

[26] National Oceanic and Atmospheric Administration (NOAA) *Global Climate Report – Annual 2018* (*last accessed* 14 February 2019) ("During 2018, 11 of 12 monthly global land and ocean temperature departures from average ranked among the five warmest for their respective months, giving way to the fourth warmest year in NOAA's 139-year record.").

[27] National Oceanic and Atmospheric Administration (NOAA) *Global Climate Report – Annual 2018* (*last accessed* 14 February 2019) ("The years 2015–2017 each had a global temperature departure from average that was more than 1.0°C (1.8°F) above the 1880–1900 average, which is a period that is commonly used to represent the pre-industrial conditions. However, 2018 was just shy of reaching the 1.0°C (1.8°F) mark at 0.97°C (1.75°F).").

[28] Hansen J., *et al.* (2017) *Global Temperature in 2016* ("The 2015–16 El Niño was weaker than the 1997–98 El Niño, as measured by the peak SST anomaly in the Niño3.4 region, but the recent El Niño was longer lasting. The longevity of tropical warmth may have contributed to the magnitude of global warming, which was larger for the recent El Niño. The most extreme warming was in the Arctic; when the Arctic is excluded from the global average, global warming relative to the trend line is slightly larger in 1998 than in 2016."); *and* Press Release, WMO, *WMO confirms 2016 as hottest year on record, about 1.1°C above pre-industrial era* (18 January 2017) ("A very powerful warming El Niño event fuelled high temperatures in the early months of 2016. But even after the end of El Niño, temperatures remained well above average. All the 16 hottest years on record have been this century, apart from 1998 when there was a strong El Niño."). The National Aeronautics and Space Administration (NASA) Goddard

Institute for Space Studies (GISS) calculated that El Niño contributed 0.12 ºC of warming in 2016. Press Release, NASA, *NASA, NOAA Data Show 2016 Warmest Year on Record Globally* (18 January 2017) ("Phenomena such as El Niño or La Niña, which warm or cool the upper tropical Pacific Ocean and cause corresponding variations in global wind and weather patterns, contribute to short-term variations in global average temperature. A warming El Niño event was in effect for most of 2015 and the first third of 2016. Researchers estimate the direct impact of the natural El Niño warming in the tropical Pacific increased the annual global temperature anomaly for 2016 by 0.2 degrees Fahrenheit (0.12 degrees Celsius)."). The recent El Niño also influenced CO_2 emissions, leading to a larger increase in 2015 to 2016 than that which was observed from 2014 to 2015 because of higher emissions from terrestrial sources and lower uptake from vegetation. World Meteorological Organization (WMO) (2018) WMO STATEMENT ON THE STATE OF THE GLOBAL CLIMATE IN 2017, 7 ("The increase in CO_2 from 2015 to 2016 was larger than the increase observed from 2014 to 2015 and the average over the last decade, and it was the largest annual increase observed in the post-1984 period. The El Niño event contributed to the increased growth rate in 2016, both through higher emissions from terrestrial sources (e.g. forest fires) and decreased uptake of CO_2 by vegetation in drought-affected areas. The El Niño event in 2015/2016 contributed to the increased growth rate through complex two-way interactions between climate change and the carbon cycle.").

[29] World Meteorological Organization (WMO), *WMO confirms 2017 among the three warmest years on record* (18 January 2018) ("In a clear sign of continuing long-term climate change caused by increasing atmospheric concentrations of greenhouse gases, 2015, 2016 and 2017 have been confirmed as the three warmest years on record. 2016 still holds the global record, whilst 2017 was the warmest year without an El Niño, which can boost global annual temperatures."); *see also* National Aeronautics and Space Administration (NASA) Goddard Institute for Space Studies (GISS), *Long-term warming trend continued in 2017: NASA, NOAA* (18 January 2018) ("In an analysis where the effects of the recent El Niño and La Niña patterns were statistically removed from the record, 2017 would have been the warmest year on record."); *and* National Oceanic and Atmospheric Administration (NOAA), *Global Climate Report - Annual 2017* (*last accessed* 28 August 2018) ("The 2017 average global temperature across land and ocean surface areas was 0.84°C (1.51°F) above the 20th century average of 13.9°C (57.0°F), behind the record year 2016 (+0.94°C / +1.69°F) and 2015 (+0.90°C / +1.62°F; second warmest year on record) both influenced by a strong El Niño episode. The year 2017 is also the warmest year without an El Niño present in the tropical Pacific Ocean."). March 2017 was the first time warming was over 1.0 ºC without the influence of El Niño. National Oceanic and Atmospheric Administration (NOAA), *Global Climate Report - Annual 2017* (*last accessed* 28 August 2018) ("[T]he global land and ocean temperature for the month of March 2017 was 1.03°C (1.9°F) above the 20th century average—this marked the first time the monthly temperature departure from average surpassed 1.0°C (1.8°F) in the absence of an El Niño episode in the tropical Pacific Ocean.").

[30] The variation between these datasets depends on the data sampled—including the extent to which the Arctic is represented—and the baseline to which the observations are compared. *See* National Aeronautics and Space Administration (NASA) Goddard Institute for Space Studies (GISS), *Long-term warming trend continued in 2017: NASA, NOAA* (18 January 2018) ("In a separate, independent analysis, scientists at the National Oceanic and Atmospheric Administration (NOAA) concluded that 2017 was the third-warmest year in their record. The minor difference in rankings is due to the different methods used by the two agencies to analyze global temperatures, although over the long-term the agencies' records remain in strong agreement. Both analyses show that the five warmest years on record all have taken place since 2010.").

[31] Press Release, NASA GISS, *2018 Fourth Warmest Year in Continued Warming Trend, According to NASA, NOAA* (6 February 2018) ("Global temperatures in 2018 were 1.5 degrees Fahrenheit (0.83 degrees Celsius) warmer than the 1951 to 1980 mean, according to scientists at NASA's Goddard Institute for Space Studies (GISS) in New York. Globally, 2018's temperatures rank behind those of 2016, 2017 and 2015. The past five years are, collectively, the warmest years in the modern record.").

[32] National Oceanic and Atmospheric Administration (NOAA), *Global Climate Report - Annual 2017* (*last accessed* 28 August 2018).

[33] Press Release, WMO, *WMO confirms past 4 years were warmest on record* (6 February 2019) ("A consolidated analysis by the World Meteorological Organization of five leading international datasets showed that the global average surface temperature in 2018 was approximately 1.0° Celsius (with a margin of error of ±0.13°C) above the pre-industrial baseline (1850-1900). It ranks as the fourth warmest year on record.").

[34] Hansen J., *et al.* (2019) *Global Temperature in 2018 and Beyond*.

[35] Henley B. J. & King A. D. (2017) *Trajectories toward the 1.5°C Paris target: Modulation by the Interdecadal Pacific Oscillation*, GEOPHYSICAL RESEARCH LETTERS 44(9): 4256–4262, 4256 ("Global temperature is rapidly approaching the 1.5°C Paris target. In the absence of external cooling influences, such as volcanic eruptions,

temperature projections are centered on a breaching of the 1.5°C target, relative to 1850–1900, before 2029. The phase of the Interdecadal Pacific Oscillation (IPO) will regulate the rate at which mean temperature approaches the 1.5°C level. A transition to the positive phase of the IPO would lead to a projected exceedance of the target centered around 2026. If the Pacific Ocean remains in its negative decadal phase, the target will be reached around 5 years later, in 2031.").

[36] Ricke K. L. and Caldeira K. (2014) *Maximum warming occurs about one decade after a carbon dioxide emission*, ENVTL. RESEARCH LETTERS 9(124002):1–8, 6 ("Our analysis implies warming from an individual carbon dioxide emission can be expected to reach its peak value within about a decade and, for the most part, persist for longer than a century. There is substantial uncertainty in both the amount and timing of this warming, and while the largest contributor to this uncertainty is equilibrium climate sensitivity, there are substantial contributions from the carbon-cycle and climate system thermal inertia."); *see also* Zickfeld K. and Herrington T. (2015) *The time lag between a carbon dioxide emission and maximum warming increases with the size of the emission*, ENVTL. RESEARCH LETTERS 10(031001):1–3, 2 ("Our results indicate that as CO_2 continues to accumulate in the atmosphere, the full warming effect of an emission may take several decades, if not centuries to emerge. A large fraction of the warming, however, will be realized relatively quickly (93% of the peak warming is realized 10 years after the emissions for the 1000 PgC pulse). This implies that the warming commitment from past CO_2 emissions is small, and that future warming will largely be determined by current and future CO_2 emissions. Each additional CO_2 emission will contribute to warming that will persist almost indefinitely. Thus, emission reductions implemented today will equally benefit current and future generations.").

[37] CARBON BRIEF, Analysis: How much 'carbon budget' is left to limit global warming to 1.5C? (9 April 2018) ("While calculations based on Earth System Models (ESMs, see below) used in the last Intergovernmental Panel on Climate Change (IPCC) report suggest that we have only a few years left at our current rate of emissions before we blow the 1.5C carbon budget, some recent studies have suggested that the remaining carbon budget is much larger.").

[38] Schurer A. P., *et al.* (2017) *Importance of the pre-industrial baseline for likelihood of exceeding Paris goals*, NATURE CLIMATE CHANGE 7:563–567, 565–566 ("The relatively small early warming can also have dramatic impacts on cumulative carbon budgets. In the most recent IPCC report, the total carbon budget allowed to avoid exceeding 1.5 ºC and 2 ºC was given as the amount of carbon emissions since 1870 that would lead to a warming relative to an 1861–1880 baseline. …The IPCC estimated that there is a 50% likelihood of keeping temperature to a 2 ºC threshold (relative to 1861–1880) if 1210 GTC is emitted since 1870 (which equates to 605 GTC per degree warming). If non-CO_2 forcings are also taken into account, under the RCP2.6 scenario, the allowed emissions of carbon reduce further to 820GTC. Given that the IPCC estimates that 515 GTC had been emitted up until 2011 (since 1870) this leaves 305 GTC still to be emitted. But, assuming linearity, if a warming of 0.1 ºC had already occurred due to CO_2 increases by 1861–1880, then around 60 GTC of the budget would have already been used. This corresponds to roughly 20% of the budget still remaining (in 2011), and approximately 40% if the early warming was as much as 0.2 ºC. The corresponding fractions of the remaining budget are likely to be even larger for a 1.5 ºC target.").

[39] Hansen J., *et al.* (2017) *Young people's burden: requirement of negative CO_2 emissions*, EARTH SYSTEMS DYNAMICS 8:577–616, 585 ("Annual increase in atmospheric CO_2, averaged over a few years, grew from less than 1 ppm yr^{-1} 50 years ago to more than 2 ppm yr^{-1} today (Fig. 6), with global mean CO_2 now exceeding 400ppm (Betts et al., 2016).").

[40] NOAA, Earth System Research Laboratory Global Monitoring Division, "The NOAA Annual Greenhouse gas index (AGGI)" (*last accessed* 2 March 2019) ("Weekly data are used to create a smoothed north-south latitude profile from which a global average is calculated (Figure 2). The atmospheric abundance of CO_2 has increased by an average of 1.81 ppm per year over the past 39 years (1979–2017). The CO_2increase 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 2.2 ppm per year during the last decade (2008–2017). The annual CO_2 increase from 1 Jan 2017 to 1 Jan 2018 was 2.3 ± 0.1 ppm (see https://www.esrl.noaa.gov/gmd/ccgg/trends/global.html), which is lower than the previous two years, but higher than the average of the previous decade, and much higher than the two decades before that.").

[41] NOAA, Earth System Research Laboratory Global Monitoring Division, "Trends in Atmospheric Carbon Dioxide" (*last accessed* 2 March 2019) (*see* "Annual Mean Global Carbon Dioxide Growth Rates" table).

[42] Solomon S., *et al.* (2009) *Irreversible climate change due to carbon dioxide emissions*, PROC. NAT'L. ACAD. SCI. 106(6):1704–1709, 1704 ("[C]limate change that takes place due to increases in carbon dioxide concentration is largely irreversible for 1,000 years after emissions stop. Following cessation of emissions, removal of atmospheric

carbon dioxide decreases radiative forcing, but is largely compensated by slower loss of heat to the ocean, so that atmospheric temperatures do not drop significantly for at least 1,000 years.").

[43] International Energy Agency (IEA), Press Release, "IEA finds CO_2 emissions flat for third straight year even as global economy grew in 2016" (17 March 2017) ("Global energy-related carbon dioxide emissions were flat for a third straight year in 2016 even as the global economy grew, according to the International Energy Agency, signaling a continuing decoupling of emissions and economic activity. This was the result of growing renewable power generation, switches from coal to natural gas, improvements in energy efficiency, as well as structural changes in the global economy.").

[44] International Energy Agency (IEA) (2018) GLOBAL ENERGY & CO_2 STATUS REPORT 2017, 1 ("Global energy-related CO_2 emissions grew by 1.4% in 2017, reaching a historic high of 32.5 gigatonnes (Gt), a resumption of growth after three years of global emissions remaining flat. The increase in CO_2 emissions, however, was not universal.").

[45] Jackson R. B., *et al.* (2018) *Global energy growth is outpacing decarbonization*, ENVTL. RESEARCH LETTERS 13(120401):1–7, 1 ("Recent reports have highlighted the challenge of keeping global average temperatures below 2 °C and—even more so—1.5 °C (IPCC 2018). Fossil-fuel burning and cement production release ~90% of all CO_2 emissions from human activities. After a three-year hiatus with stable global emissions (Jackson *et al* 2016; Le Quéré C *et al* 2018a ; IEA 2018), CO_2 emissions grew by 1.6% in 2017 to 36.2 Gt (billion tonnes), and are expected to grow a further 2.7% in 2018 (range: 1.8%–3.7%) to a record 37.1 ± 2 Gt CO_2 (Le Quéré *et al* 2018b). Additional increases in 2019 remain uncertain but appear likely because of persistent growth in oil and natural gas use and strong growth projected for the global economy. Coal use has slowed markedly in the last few years, potentially peaking, but its future trajectory remains uncertain. Despite positive progress in ~19 countries whose economies have grown over the last decade and their emissions have declined, growth in energy use from fossil-fuel sources is still outpacing the rise of low-carbon sources and activities. A robust global economy, insufficient emission reductions in developed countries, and a need for increased energy use in developing countries where per capita emissions remain far below those of wealthier nations will continue to put upward pressure on CO_2 emissions. Peak emissions will occur only when total fossil CO_2 emissions finally start to decline despite growth in global energy consumption, with fossil energy production replaced by rapidly growing low- or no-carbon technologies.").

[46] International Energy Agency (IEA) (2018) GLOBAL ENERGY & CO_2 STATUS REPORT 2017, 3 ("Global energy-related CO_2 emissions rose by 1.4% in 2017, an increase of 460 million tonnes (Mt), and reached a historic high of 32.5 Gt. Last year's growth came after three years of flat emissions and contrasts with the sharp reduction needed to meet the goals of the Paris Agreement on climate change. The increase in carbon emissions, equivalent to the emissions of 170 million additional cars, was the result of robust global economic growth of 3.7%, lower fossil-fuel prices and weaker energy efficiency efforts. These three factors contributed to pushing up global energy demand by 2.1% in 2017.").

[47] Zeebe R. E., *et al.* (2016) *Anthropogenic carbon release rate unprecedented during the past 66 million years*, NATURE GEOSCIENCE 9:325–329, 328 ("The initial carbon release during the PETM onset thus occurred over at least 4,000 yr. Using estimates of 2,500–4,500 Pg C for the initial carbon release, the maximum sustained PETM carbon release rate was therefore 0.6–1.1 Pg C yr^{-1}. Given currently available palaeorecords, we conclude that the present anthropogenic carbon release rate (~10 Pg C yr^{-1}) is unprecedented during the Cenozoic (past 66 Myr). Possible known consequences of the rapid man-made carbon emissions have been extensively discussed elsewhere. Regarding impacts on ecosystems, the present/future rate of climate change and ocean acidification is too fast for many species to adapt, which is likely to result in widespread future extinctions in marine and terrestrial environments that will substantially exceed those at the PETM (ref. 13). Given that the current rate of carbon release is unprecedented throughout the Cenozoic, we have effectively entered an era of a no-analogue state, which represents a fundamental challenge to constraining future climate projections.").

[48] Arctic Monitoring and Assessment Programme (AMAP) (2017) SNOW, WATER, ICE, AND PERMAFROST IN THE ARCTIC: SUMMARY FOR POLICYMAKERS, 8 ("The Arctic is still a cold place, but it is warming faster than any other region on Earth. Over the past 50 years, the Arctic's temperature has risen by more than twice the global average. Increasing concentrations of greenhouse gases in the atmosphere are the primary underlying cause: the heat trapped by greenhouse gases triggers a cascade of feedbacks that collectively amplify Arctic warming.").

[49] Bindoff N. L., *et al.* (2013) CHAPTER 10: DETECTION AND ATTRIBUTION OF CLIMATE CHANGE: FROM GLOBAL TO REGIONAL, *in* IPCC (2013) CLIMATE CHANGE 2013: THE PHYSICAL SCIENCE BASIS, Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 906 ("Of principal importance is 'Arctic Amplification' (see Box 5.1) where surface temperatures in the Arctic are increasing faster than elsewhere in the world."); *see also* Francis J. A. & Vavrus S. J. (2015) *Evidence for a wavier jet stream in response to rapid*

Arctic warming, ENVTL. RESEARCH LETTERS 10(014005):1–12, 1 ("This paper builds on the proposed linkage between Arctic amplification (AA)—defined here as the enhanced sensitivity of Arctic temperature change relative to mid-latitude regions—and changes in the large-scale, upper-level flow in mid-latitudes. Widespread Arctic change continues to intensify, as evidenced by continued loss of Arctic sea ice; decreasing mass of Greenland's ice sheet, rapid decline of snow cover on Northern hemisphere continents during early summer, and the continued rapid warming of the Arctic relative to midlatitudes. While these events are driven by AA, they also amplify it: melting ice and snow expose the dark surfaces beneath, which reduces the surface albedo, further enhances the absorption of insolation, and exacerbates melting. Expanding ice-free areas in the Arctic Ocean also lead to additional evaporation that augments warming and Arctic precipitation.").

[50] Overland J. E., *et al.* (2018) *Surface Air Temperature*, *in* ARCTIC REPORT CARD 2018, 6 ("Currently there is no consensus on understanding the full reasons for Arctic amplification. Proposed mechanisms for Arctic amplification include: reduced summer albedo due to sea ice and snow cover loss; the increase of total water vapor content in the Arctic atmosphere; changes in cloudiness, and changes in pollution (Pithan and Mauritsen, 2014; Kim et al., 2017; Acosta Navarro et al., 2016; Dufour et al., 2016)."); *see also* Overland J. E., *et al.* (2017) *Surface air temperature, in* ARCTIC REPORT CARD 2017 ("The greater rate of Arctic temperature increase, compared to the global mean increase, is referred to as Arctic Amplification. Mechanisms for Arctic Amplification include: reduced summer albedo, due to sea ice and snow cover loss; the increase of total water vapor content in the Arctic atmosphere; a summer decrease and winter increase in total cloudiness (Makshtas et al., 2011; Lenaerts et al., 2017); the additional heat generated by newly sea-ice free ocean areas that are maintained later into the autumn (Serreze and Barry, 2011); and the lower rate of heat loss to space in the Arctic relative to the subtropics, due to lower mean surface temperatures in the Arctic (Pithan and Mauritsen, 2014). Arctic warming has also been influenced by past air pollution reductions in Europe (Acosta Navarro et al., 2016).").

[51] Arctic Monitoring and Assessment Programme (AMAP) (2017) SNOW, WATER, ICE, AND PERMAFROST IN THE ARCTIC: SUMMARY FOR POLICYMAKERS, 3 ("The Arctic was warmer from 2011 to 2015 than at any time since instrumental records began in around 1900, and has been warming more than twice as rapidly as the world as a whole for the past 50 years. January 2016 in the Arctic was 5°C warmer than the 1981–2010 average for the region, a full 2°C higher than the previous record set in 2008, and monthly mean temperatures in October through December 2016 were 6°C higher than average for these months. Sea temperatures are also increasing, both near the surface and in deeper water.").

[52] Arctic Monitoring and Assessment Programme (AMAP) (2017) SNOW, WATER, ICE, AND PERMAFROST IN THE ARCTIC: SUMMARY FOR POLICYMAKERS, 5 ("Models project that autumn and winter temperatures in the Arctic will increase to 4–5°C above late 20th century values before mid-century, under either a medium or high greenhouse gas concentration scenario. This is twice the increase projected for the Northern Hemisphere.").

[53] Francis J. A. & Vavrus S. J. (2015) *Evidence for a wavier jet stream in response to rapid Arctic warming*, ENVTL. RESEARCH LETTERS 10(014005):1–12, 8 ("Overall, the pattern of frequency change is consistent with expectations of a more amplified jet stream in response to rapid Arctic warming. Amplified jet-stream patterns are associated with a variety of extreme weather events (i.e., persistent heat, cold, wet, and dry), thus an increase in amplified patterns suggests that these types of extreme events will become more frequent in the future as AA continues to intensify in all seasons. These results may also provide a mechanism to explain observed associations between sea-ice loss and continental heat waves, cold spells, heavy snowfall, and anomalous summer precipitation patterns in Europe.").

[54] Shepherd T. G. (2016) *Effects of a warming Arctic*, SCIENCE 353(6303):989–990, 989 ("Weather systems provide most of the heat transport from mid- to high latitudes during winter. In some years, a strong tropospheric polar vortex inhibits the exchange of air masses between the Arctic and mid-latitudes. In other years, a weaker and wavier polar vortex enhances the exchange, leading to mid-latitude cold spells and a warmer Arctic (see the first figure). An increased tendency for the latter state results in a trend toward cold continents and a warm Arctic, although North America and Eurasia can vary independently. Such a trend is seen in recent decades, with a cooling tendency over the eastern United States and, especially, central Asia and an accelerated warming of the Arctic compared with that seen over the past 50 years.").

[55] Tedesco M., *et al.* (2016) *Arctic cut-off high drives the poleward shift of a new Greenland melting record*, NATURE COMMUNICATIONS 7(11723):1–6, 4 ("Although recent melt records over the Greenland have been linked to exceptional mid-tropospheric atmospheric conditions, with episodes of atmospheric blocking ridges being associated with Greenland's melting extremes, little or no attention has been given to the impact of the anticipated effects of Arctic amplification on the surface mass balance of the Greenland ice sheet. In this regard, the 2015 records for both the 500hPa zonal winds and the maximum ridging latitude are consistent with the proposed effects on upper level

atmosphere characteristics associated with Arctic amplification. … Our work presented here demonstrates a strong need to identify the mechanisms that create and maintain strong cutoff highs. The new atmospheric records, and the trends of mean zonal winds and wave amplitude of the jet stream are consistent with the suggested effects of Arctic amplification. Recent studies provide theoretical arguments that slowing zonal winds might be associated with larger planetary wave amplitudes and that Arctic amplification and/or sea-ice loss do intensify existing ridges, thereby contributing to their persistence."); *see also* PhysOrg, *Greenland sets melt records in 2015 consistent with 'Arctic amplification'* (9 June 2016) ("Arctic amplification is the faster warming of the Arctic compared to the rest of the Northern Hemisphere as sea ice disappears. It is fuelled by a feedback loop: rising global temperatures are melting Arctic sea ice, leaving dark open water that absorbs more solar radiation which in turn warms the Arctic even more. Arctic amplification is well documented, but its effects on the atmosphere are more widely debated. … 'If loss of sea ice is driving changes in the jet stream, the jet stream is changing Greenland, and this, in turn, has an impact on the Arctic system as well as the climate. It's a system, it is strongly interconnected and we have to approach it as such.'").

[56] Tedesco M., *et al.* (2016) *Arctic cut-off high drives the poleward shift of a new Greenland melting record*, NATURE COMMUNICATIONS 7(11723):1–6, 1 ("Here, using reanalysis data and the outputs of a regional climate model, we show that the persistence of an exceptional atmospheric ridge, centred over the Arctic Ocean, was responsible for a poleward shift of runoff, albedo and surface temperature records over the Greenland during the summer of 2015. New records of monthly mean zonal winds at 500hPa and of the maximum latitude of ridge peaks of the 5,700±50m isohypse over the Arctic were associated with the formation and persistency of a cutoff high. The unprecedented (1948–2015) and sustained atmospheric conditions promoted enhanced runoff, increased the surface temperatures and decreased the albedo in northern Greenland, while inhibiting melting in the south, where new melting records were set over the past decade."); *see also* USA TODAY, D. Rice, *Arctic's melting ice creates vicious warming circle* (9 June 2016) ("Arctic sea ice hit a record low in May as scientists discovered the first-ever link between melting ice in Greenland and a phenomenon known to warm the area faster than the rest of the Northern Hemisphere. The occurrence is called 'Arctic amplification' and until now, scientists didn't know Greenland was linked to it, according to a study published Thursday in the British journal Nature Communications. The phenomenon is fueled by a feedback loop where rising temperatures melt Arctic sea ice, which leaves dark open water that absorbs more warmth from the sun, thereby warming the Arctic even more. White frozen ice, on the other hand, would reflect sunlight back into space. The study comes two days after scientists announced the average area of Arctic sea ice in May was 4.63 million square miles, about a half million square miles below average. That level sets the stage for new record lows in the coming months.").

[57] Boucher O., *et al.* (2013) CHAPTER 7: CLOUDS AND AEROSOLS, *in* IPCC (2013) CLIMATE CHANGE 2013: THE PHYSICAL SCIENCE BASIS, Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 580 ("The effect of clouds on the Earth's present-day top of the atmosphere (TOA) radiation budget, or cloud radiative effect (CRE), can be inferred from satellite data by comparing upwelling radiation in cloudy and non-cloudy conditions (Ramanathan et al., 1989). By enhancing the planetary albedo, cloudy conditions exert a global and annual shortwave cloud radiative effect (SWCRE) of approximately –50 W m^{-2} and, by contributing to the greenhouse effect, exert a mean longwave effect (LWCRE) of approximately +30 W m^{-2}, with a range of 10% or less between published satellite estimates (Loeb et al., 2009). Some of the apparent LWCRE comes from the enhanced water vapour coinciding with the natural cloud fluctuations used to measure the effect, so the true cloud LWCRE is about 10% smaller (Sohn et al., 2010). The net global mean CRE of approximately –20 W m^{-2} implies a net cooling with a range of 10% or less between published satellite estimates (Loeb et al., 2009). Some of the apparent LWCRE comes from the enhanced water vapour coinciding with the natural cloud fluctuations used to measure the effect, so the true cloud LWCRE is about 10% smaller (Sohn et al., 2010). The net global mean CRE of approximately –20 W m^{-2} implies a net cooling effect of clouds on the current climate. Owing to the large magnitudes of the SWCRE and LWCRE, clouds have the potential to cause significant climate feedback (Section 7.2.5). The sign of this feedback on climate change cannot be determined from the sign of CRE in the current climate, but depends instead on how climate-sensitive the properties are that govern the LWCRE and SWCRE."); *see also* Norris J. R., *et al.* (2016) *Evidence for climate change in the satellite cloud record*, NATURE 536:72–75, 72 ("Here we show that several independent, empirically corrected satellite records exhibit large-scale patterns of cloud change between the 1980s and the 2000s that are similar to those produced by model simulations of climate with recent historical external radiative forcing. Observed and simulated cloud change patterns are consistent with poleward retreat of mid-latitude storm tracks, expansion of subtropical dry zones, and increasing height of the highest cloud tops at all latitudes. The primary drivers of these cloud changes appear to be increasing greenhouse gas concentrations and a recovery from volcanic radiative cooling. These results indicate that the cloud changes

most consistently predicted by global climate models are currently occurring in nature."); Bender F. A.-M., *et al.* (2012) *Changes in extratropical storm track cloudiness 1983–2008: observational support for a poleward shift*, CLIMATE DYNAMICS 38(9–10):2037–2053, 2037 ("Climate model simulations suggest that the extratropical storm tracks will shift poleward as a consequence of global warming. In this study the northern and southern hemisphere storm tracks over the Pacific and Atlantic ocean basins are studied using observational data, primarily from the International Satellite Cloud Climatology Project, ISCCP. …It is found that the storm tracks, here represented by the extent of the mid-latitude-centered band of maximum cloud cover over the studied ocean basins, experience a poleward shift as well as a narrowing over the 25 year period covered by ISCCP. … The observed changes in storm track cloudiness can be related to local cloud-induced changes in radiative forcing, using ERBE and CERES radiative fluxes. The shortwave and the longwave components are found to act together, leading to a positive (warming) net radiative effect in response to the cloud changes in the storm track regions, indicative of positive cloud feedback. Among the CMIP3 models that simulate poleward shifts in all four storm track areas, all but one show decreasing cloud amount on a global mean scale in response to increased CO_2 forcing, further consistent with positive cloud feedback. Models with low equilibrium climate sensitivity to a lesser extent than higher-sensitivity models simulate a poleward shift of the storm tracks."); *and* Committee to Prevent Extreme Climate Change (2017) *Well Under 2 Degrees Celsius: Fast Action Policies to Protect People and the Planet from Extreme Climate Change*, 9 ("Though clouds enhance the greenhouse effect by trapping heat, they also reflect an enormous amount of solar radiation and nearly double the albedo of the planet. Their albedo effect dominates over their greenhouse effect, balancing out to a net cooling of about –25 Wm^{-2} (compared with the 1.6 Wm^{-2} forcing from CO_2 and total current forcing of 3 Wm^{-2}) (IPCC, 2013). More than two-thirds of this cooling is from the extensive extratropical cloud systems, which are found poleward of about 40° and are associated with jet streams and storm tracks (IPCC, 2013). Satellite data reveal that these cloud systems are retreating poleward in both hemispheres, which has led to an increase in the solar radiation reaching the extratropics, further amplifying warming (Bender et al., 2012; Norris et al., 2016). Thus, the Arctic warming is amplified by two large feedbacks: first is the decrease in albedo from the retreating sea ice, which is then further amplified by the decrease in albedo from the shrinking storm track clouds.").

[58] Boucher O., *et al.* (2013) CHAPTER 7: CLOUDS AND AEROSOLS, *in* IPCC (2013) CLIMATE CHANGE 2013: THE PHYSICAL SCIENCE BASIS, Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 582 ("Owing to the large magnitudes of the SWCRE and LWCRE, clouds have the potential to cause significant climate feedback (Section 7.2.5). The sign of this feedback on climate change cannot be determined from the sign of CRE in the current climate, but depends instead on how climate-sensitive the properties are that govern the LWCRE and SWCRE.").

[59] Boucher O., *et al.* (2013) CHAPTER 7: CLOUDS AND AEROSOLS, *in* IPCC (2013) CLIMATE CHANGE 2013: THE PHYSICAL SCIENCE BASIS, Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 588("Changes in predicted cloud cover geographically correlate with simulated subtropical drying (Meehl et al., 2007), suggesting that they are partly tied to large-scale circulation changes including the poleward shifts found in most models (Wetherald and Manabe, 1980; Sherwood et al., 2010b; Section 2.7). Bender et al. (2012) and Eastman and Warren (2013) report poleward shifts in cloud since the 1970s consistent with those reported in other observables (Section 2.5.6) and simulated by most GCMs, albeit with weaker amplitude (Yin, 2005). This shift of clouds to latitudes of weaker sunlight decreases the planetary albedo and would imply a strong positive feedback if it were due to global warming (Bender et al., 2012), although it is probably partly driven by other factors (Section 10.3). The true amount of positive feedback coming from poleward shifts therefore remains highly uncertain, but is underestimated by GCMs if, as suggested by observational comparisons, the shifts are underestimated (Johanson and Fu, 2009; Allen et al., 2012).").

[60] Norris J. R., *et al.* (2016) *Evidence for climate change in the satellite cloud record*, NATURE 536:72–75, 74 ("Both the GHG and the NAT simulations experience increasing tropospheric temperature and decreasing stratospheric temperature from the 1980s and the 2000s. … Tropospheric warming and stratospheric cooling promote an increase in the height of the highest cloud tops, and together with global warming, promote an expansion of the tropical zone and a poleward shift of storm tracks. … The expansion of subtropical dry zones results in less reflection of solar radiation back to space. As cloud tops rise, their greenhouse effect becomes stronger. Both of these cloud changes have a warming effect on climate. Our results suggest that radiative forcing by a combination of anthropogenic greenhouse gases and volcanic aerosol has produced observed cloud changes during the past several decades that

exert positive feedbacks on the climate system. We expect that increasing greenhouse gases will cause these cloud trends to continue in the future, unless offset by unpredictable large volcanic eruptions.").

[61] 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, 14245 ("The observed increase in the concentration of greenhouse gases (GHGs) since the preindustrial era has most likely committed the world to a warming of 2.4°C (1.4°C to 4.3°C) above the preindustrial surface temperatures. The committed warming is inferred from the most recent Intergovernmental Panel on Climate Change (IPCC) estimates of the greenhouse forcing and climate sensitivity. The estimated warming of 2.4°C is the equilibrium warming above preindustrial temperatures that the world will observe even if GHG concentrations are held fixed at their 2005 concentration levels but without any other anthropogenic forcing such as the cooling effect of aerosols."); *and* Ramanathan V. & Xu Y. (2010) *The Copenhagen Accord for limiting global warming: Criteria, constraints, and available avenues*, PROC. NAT'L. ACAD. SCI. 107(18):8055–8062, 8056 ("CO_2 (1.65 Wm^{-2}) and the non-CO_2 GHGs (1.35 Wm^{-2}) have added 3 (range: 2.6–3.5) Wm^{-2} of radiant energy since preindustrial times. The non-CO_2 GHGs are methane (CH_4); nitrous oxide (N_2O); and halocarbons (HCs), which include CFCs, HCFCs, HFCs; and ozone in the troposphere. The 3-Wm^{-2} energy should have led to a warming of 2.4 °C. The observed warming trend (as of 2005) is only about 0.75 °C, or 30% of the expected warming. Observations of trends in ocean heat capacity as well as coupled ocean–atmosphere models suggest that about 20% (0.5 °C warming) is still stored in the oceans. The rest of the 50% involves aerosols or particles added by air pollution. BC aerosols in soot absorb solar radiation and add 0.5 (inner white circle) to 0.9 Wm^{-2}. SON_Mix of particles from fossil fuel and biomass combustion act like mirrors and reflect solar radiation back to space (−2.1 Wm^{-2}; the transparent blue-shaded circle). The resulting dimming effect at the surface has been observed in land stations around the world. The net aerosol masking effect (−2.1 + 0.9 = −1.2 Wm^{-2}), along with the 0.2-Wm^{-2} cooling by land surface changes, accounts for the missing 50% of the warming by GHGs. There is at least a 3-fold uncertainty in current estimates of the aerosol masking effect (the inner and outer circle of the net forcing in the figure), which has significant implications for 21st century warming as explained later.").

[62] Westervelt D. M., *et al.* (2015) *Radiative forcing and climate response to projected 21st century aerosol decreases*, ATMOS. CHEM. PHYS. 15:12681–12703, 12688 ("Future changes (mostly decreases) in aerosol emissions and aerosol amount and optical depth lead to changes in Earth's radiative balance.… From 1860 until present day, the increasing abundance of atmospheric aerosols led to a larger (more negative) aerosol forcing, peaking near present day. Preindustrial to present day aerosol forcing simulated by CM3 is about −1.8 Wm^{-2}. This large negative forcing has offset or "masked" some of the positive forcing from greenhouse gases. Although the net forcing is still positive, without the large increase in the 20th century of aerosol emissions, the net positive forcing would be much larger.").

[63] Lamarque J.-F., *et al.* (2011) *Global and regional evolution of short-lived radiatively-active gases and aerosols in the Representative Concentration Pathways*, CLIMATIC CHANGE 109:191–212, 200 ("The main contributor (at the global scale) to aerosol radiative forcing between pre-industrial and 2000 is sulfate (Schulz et al. 2006)."); *see also* van Vuuren D. P., *et al.* (2011) *RCP2.6: Exploring the Possibility to Keep Global mean Temperature Increase Below 2ºC*, CLIMATIC CHANGE 109:95–116, 109 ("The changes in SO_2 emissions are relevant for environmental acidification concerns, but also for climate change, as SO_2 aerosols partly offset the radiative forcing of greenhouse gases.").

[64] Bond T. C., *et al.* (2013) *Bounding the role of black carbon in the climate system: A scientific assessment*, J. GEOPHYSICAL RESEARCH–ATMOSPHERES 118(11):5380–5552, 5385 ("Black carbon undergoes regional and intercontinental transport during its short atmospheric lifetime. Atmospheric removal occurs within a few days to weeks via precipitation and contact with surfaces. As a result, black carbon is found in remote regions of the atmosphere at concentrations much lower than in source regions.").

[65] Bond T. C., *et al.* (2013) *Bounding the role of black carbon in the climate system: A scientific assessment*, J. GEOPHYSICAL RESEARCH–ATMOSPHERES 118(11):5380–5552, 5387–5388 ("The 100year global-warming-potential (GWP) value for black carbon is 900 (120 to 1800 range) with all forcing mechanisms included. The large range derives from the uncertainties in the climate forcings for black carbon effects. The GWP and other climate metric values vary by about ±30% between emitting regions. Black-carbon metric values decrease with increasing time horizon due to the short lifetime of black carbon emissions compared to CO_2. Black carbon and CO_2 emission amounts with equivalent 100 year GWPs have different impacts on climate, temperature, rainfall, and the timing of these impacts. These and other differences raise questions about the appropriateness of using a single metric to compare black carbon and greenhouse gases.").

[66] Bond T. C., *et al.* (2013) *Bounding the role of black carbon in the climate system: A scientific assessment*, J. GEOPHYSICAL RESEARCH–ATMOSPHERES 118(11):5380–5552, 5385–5386 ("Direct radiative forcing of black carbon

is caused by absorption and scattering of sunlight. Absorption heats the atmosphere where black carbon is present and reduces sunlight that reaches the surface and that is reflected back to space. Direct radiative forcing is the most commonly cited climate forcing associated with black carbon. … Black carbon influences the properties of ice clouds and liquid clouds through diverse and complex processes. These processes include changing the number of liquid cloud droplets, enhancing precipitation in mixed-phase clouds, and changing ice particle number and cloud extent. The resulting radiative changes in the atmosphere are considered climate indirect effects of black carbon.").

[67] Bond T. C., *et al.* (2013) *Bounding the role of black carbon in the climate system: A scientific assessment*, J. GEOPHYSICAL RESEARCH–ATMOSPHERES 118(11):5380–5552, 5384–5385 ("Black carbon is co-emitted with a variety of other aerosols and aerosol precursor gases. Soon after emission, black carbon becomes mixed with other aerosol components in the atmosphere. This mixing increases light absorption by black carbon, increases its ability to form liquid-cloud droplets, alters its capacity to form ice nuclei, and, thereby, influences its atmospheric removal rate. …The largest global sources are open burning of forests and savannas. Dominant emitters of black carbon from other types of combustion depend on the location. Residential solid fuels (i.e., coal and biomass) contribute 60 to 80% of Asian and African emissions, while on-road and off-road diesel engines contribute about 70% of emissions in Europe, North America, and Latin America. Residential coal is a significant source in China, the former USSR, and a few Eastern European countries. These categories represent about 90% of black-carbon mass emissions. Other miscellaneous black-carbon-rich sources, including emissions from aviation, shipping, and flaring, account for another 9%, with the remaining 1% attributable to sources with very low black carbon emissions.").

[68] Feng Y., *et al.* (2013) *Brown carbon: a significant atmospheric absorber of solar radiation?*, ATMOS. CHEM. & PHYS. 13:8607–8621, 8608 ("Recently, optical and thermal analysis (e.g., Kirchstetter et al., 2004; Chen and Bond, 2010) and electron microscopy (e.g., Alexander et al., 2008) from laboratory and field experiments have provided strong evidence for the existence of some organic carbon (OC) with light absorbing properties. This fraction of absorbing OC, known as brown carbon (BrC) for its light brownish color, absorbs strongly in the ultraviolet wavelengths and less significantly going into the visible (Kirchstetter et al., 2004; Hoffer et al., 2006). Types of BrC include tar materials from smoldering fires or solid fuel combustion (Bond, 2001; Alexander et al., 2008), pyrolysis products from biomass burning (Mukai and Ambe, 1986), or humic-like substances from soil or biogenic emissions (Limbeck et al., 2003). Depending on its origins, the absorption efficiency and spectral dependence of BrC varies (Andreae and Gelencsér, 2006). A few recent observationally based studies indicated an abundance of BrC in the atmosphere, which could enhance solar radiation absorption and reduce surface radiative flux substantially (Chung et al., 2012; Bahadur et al., 2012).").

[69] Feng Y., *et al.* (2013) *Brown carbon: a significant atmospheric absorber of solar radiation?*, ATMOS. CHEM. & PHYS. 13:8607–8621, 8618 ("By integrating ground-based aerosol data with field and satellite observations, Chung et al. (2012) found that the global OA radiative forcing is close to zero when the contribution of BrC is implicitly included in the aerosol absorption spectrum. However, whether the BrC absorption could play a significant role in global and regional direct radiative forcing of carbonaceous aerosols remains uncertain.").

[70] 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 [Atmospheric Brown Cloud] masking effect, it may speed up the approach to the committed warming of 2.4°C (1.4–4.3°C). We are not arguing in favor of more coal combustion (a major contributor to ABCs) but simply point out that increasing natural gas consumption by 70% from 2005 to 2030 as projected now by the International Energy Agency (19) without an overall reduction in fossil fuel consumption could significantly accelerate the warming."); *see also* Westervelt D. M., *et al.* (2015) *Radiative forcing and climate response to projected 21st century aerosol decreases*, ATMOS. CHEM. PHYS. 15:12681–12703, 12681–12682 ("It is widely expected that global emissions of atmospheric aerosols and their precursors will decrease strongly throughout the remainder of the 21st century, due to emission reduction policies enacted to protect human health. For instance, global emissions of aerosols and their precursors are projected to decrease by as much as 80 % by the year 2100, according to the four Representative Concentration Pathway (RCP) scenarios. The removal of aerosols will cause unintended climate consequences, including an unmasking of global warming from long-lived greenhouse gases….We find that the projected global radiative forcing and climate response due to aerosol decreases do not vary significantly across the four RCPs by 2100, although there is some mid-century variation, especially in cloud droplet effective radius, that closely follows the RCP emissions and energy consumption projections. Up to 1 W m−2 of radiative forcing may be unmasked globally from 2005 to 2100 due to reductions in aerosol and precursor emissions, leading to average global temperature increases up to 1 K and global precipitation rate increases up to 0.09 mm day^{-1} ….**The expected unmasking of**

global warming caused by aerosol reductions will require more aggressive greenhouse gas mitigation policies than anticipated in order to meet desired climate targets. …While clearly beneficial for human health, declining aerosol emissions will result in the unintended consequence of unmasking additional climate warming, due to the reduction of the cooling effects from anthropogenic aerosols such as sulfate and organic carbon (OC). Thus, careful policy implementation is necessary in order to maximize reduction of unhealthy air pollution while also minimizing the unmasking of additional global warming." [emphasis added]).

[71] Kopp R. E., *et al.* (2016) *Tipping elements and climate–economic shocks: Pathways toward integrated assessment*, EARTH'S FUTURE 4:346–372; *see also* Lenton T. M., *et al.* (2008) *Tipping elements in the Earth's climate system*, PROC. NAT'L. ACAD. SCI. 105(6):1786–1793; *and* Steffen W., *et al.* (2018) *Trajectories of the Earth System in the Anthropocene*, PROC. NAT'L. ACAD. SCI. 115(33):8252–8259, 8255, Figure 3.

[72] World Meteorological Organization (WMO) (2018) WMO STATEMENT ON THE STATE OF THE GLOBAL CLIMATE IN 2017, 4 ("Global mean temperatures in 2017 were 1.1 °C ± 0.1 °C above pre-industrial levels. Whilst 2017 was a cooler year than the record-setting 2016, it was still one of the three warmest years on record, and the warmest not in uenced by an El Niño event. The average global temperature for 2013–2017 is close to 1 °C above that for 1850–1900 and is also the highest five-year average on record.")

[73] Drijfhout S., *et al.* (2015) *Catalogue of abrupt shifts in Intergovernmental Panel on Climate Change climate models*, PROC. NAT'L. ACAD. SCI. 112(43):E5777–E5786, E5777 ("Abrupt transitions of regional climate in response to the gradual rise in atmospheric greenhouse gas concentrations are notoriously difficult to foresee. However, such events could be particularly challenging in view of the capacity required for society and ecosystems to adapt to them. We present, to our knowledge, the first systematic screening of the massive climate model ensemble informing the recent Intergovernmental Panel on Climate Change report, and reveal evidence of 37 forced regional abrupt changes in the ocean, sea ice, snow cover, permafrost, and terrestrial biosphere that arise after a certain global temperature increase. Eighteen out of 37 events occur for global warming levels of less than 2°, a threshold sometimes presented as a safe limit."); *see also* Schellnhuber H. J., *et al.* (2016) *Why the right climate target was agreed in Paris*, NATURE CLIMATE CHANGE 6:649–653, 650 ("[E]ven if global warming is limited to below 2 °C, some important tipping elements may already be harmed or transformed. In fact, the tipping point for marine ice sheet instability in the Amundsen Basin of West Antarctica may well have been crossed already, and the risk of crossing further tipping points will increase with future warming.").

[74] Kopp R. E., *et al.* (2017) *Potential surprises – compound extremes and tipping elements*, *in* CLIMATE SCIENCE SPECIAL REPORT: FOURTH NATIONAL CLIMATE ASSESSMENT, VOLUME I ("Negative feedbacks, or self-stabilizing cycles, within and between components of the Earth system can dampen changes (Ch. 2: Physical Drivers of Climate Change). However, their stabilizing effects render such feedbacks of less concern from a risk perspective than positive feedbacks, or self-reinforcing cycles. Positive feedbacks magnify both natural and anthropogenic changes. Some Earth system components, such as arctic sea ice and the polar ice sheets, may exhibit thresholds beyond which these self-reinforcing cycles can drive the component, or the entire system, into a radically different state.").

[75] Lenton T. (2013) *Environmental Tipping Points*, ANNUAL REVIEW ENV'T. & RESOURCE 38:1–29, 15 ("The loss of Arctic summer sea ice is readily reversible in models in the dark polar winter, leading many to argue that it does not possess a bifurcation-type tipping point. However, cloud feedbacks could create a bifurcation on the way to summer ice loss. Furthermore, there has already been an abrupt and persistent increase in the amplitude of seasonal ice loss since 2007. This is likely linked to the flushing of thick multiyear ice out of the basin in 2007, leaving a thinner ice cap that is prone to larger retreats each summer. The ice loss is already changing atmospheric circulation patterns and contributing to extreme weather in the midlatitudes.").

[76] Arctic Monitoring and Assessment Programme (AMAP) (2017) SNOW, WATER, ICE, AND PERMAFROST IN THE ARCTIC: SUMMARY FOR POLICYMAKERS, 8 ("Since 2011, evidence for the Arctic's evolution toward a new state has grown stronger. Additional years of data show continued or accelerating trends in record warm temperatures, changes in sea ice and snow, melting of glaciers and ice sheets, freshening and warming of the Arctic Ocean, thawing of permafrost, and widespread ecological changes.").

[77] Strauss B. H., *et al.* (2015) *Carbon choices determine US cities committed to futures below sea level*, PROC. NAT'L. ACAD. SCI. 112(44):13508–13513, 13510 ("Remote sensing studies indicate accelerating decay, plus bedrock topography favorable to collapse, for the Thwaites and Pine Island glaciers, two linchpins of the WAIS. Recent modeling work also points toward future collapse, even at reduced rates of warming and decay from the present. Topographic analysis together with theory and expert judgment indicate that the highly interconnected marine component of West Antarctica is prone to marine ice sheet instability that would spread throughout the entire basin following the disintegration of the Thwaites and Pine Island glaciers."); *see also* Favier L., *et al.* (2014)

Retreat of Pine Island Glacier controlled by marine ice-sheet instability, NATURE CLIMATE CHANGE 4:117–121, 117 ("Here, using three state-of-the-art ice-flow models, we show that Pine Island Glacier's grounding line is probably engaged in an unstable 40 km retreat. The associated mass loss increases substantially over the course of our simulations from the average value of 20 Gt yr^{-1} observed for the 1992–2011 period, up to and above 100 Gt yr^{-1}, equivalent to 3.5–10 mm eustatic sea-level rise over the following 20 years. Mass loss remains elevated from then on, ranging from 60 to 120 Gt yr^{-1}."); *and* Feldmann J. & Levermann A. (2015) *Collapse of the West Antarctic Ice Sheet after local destabilization of the Amundsen Basin*, PROC. NAT'L. ACAD. SCI. 112(46):14191–14196, 14191 ("The future evolution of the Antarctic Ice Sheet represents the largest uncertainty in sea-level projections of this and upcoming centuries. Recently, satellite observations and high-resolution simulations have suggested the initiation of an ice-sheet instability in the Amundsen Sea sector of West Antarctica, caused by the last decades' enhanced basal ice-shelf melting. Whether this localized destabilization will yield a full discharge of marine ice from West Antarctica, associated with a global sea-level rise of more than 3 m, or whether the ice loss is limited by ice dynamics and topographic features, is unclear. Here we show that in the Parallel Ice Sheet Model, a local destabilization causes a complete disintegration of the marine ice in West Antarctica. In our simulations, at 5-km horizontal resolution, the region disequilibrates after 60 y of currently observed melt rates. Thereafter, the marine ice-sheet instability fully unfolds and is not halted by topographic features. In fact, the ice loss in Amundsen Sea sector shifts the catchment's ice divide toward the Filchner–Ronne and Ross ice shelves, which initiates grounding-line retreat there. Our simulations suggest that if a destabilization of Amundsen Sea sector has indeed been initiated, Antarctica will irrevocably contribute at least 3 m to global sea-level rise during the coming centuries to millennia.").

[78] Lenton T., *et al.* (2008) *Tipping elements in the Earth's climate system*, PROC. NAT'L. ACAD. SCI. 105(6):1786–1793, 1786 ("In discussions of global change, the term tipping point has been used to describe a variety of phenomena, including the appearance of a positive feedback, reversible phase transitions, phase transitions with hysteresis effects, and bifurcations where the transition is smooth but the future path of the system depends on the noise at a critical point. We offer a formal definition, introducing the term ''tipping element'' to describe subsystems of the Earth system that are at least subcontinental in scale and can be switched—under certain circumstances— into a qualitatively different state by small perturbations. The tipping point is the corresponding critical point—in forcing and a feature of the system—at which the future state of the system is qualitatively altered."); *see also* Kopp R. E., *et al.* (2016) *Tipping elements and climate–economic shocks: Pathways toward integrated assessment*, EARTH'S FUTURE 4:346–372, 347 ("*Lenton et al*. [2008] formalized the concept of "tipping points" in the climate system in a way that loosened this definition. *Lenton et al*. [2008] defined a "tipping element" as a subsystem of the Earth system, subcontinental or larger, that small perturbations can shift into multiple different stable states. A tipping element's tipping point is a critical threshold at which "a small change in forcing triggers a strongly nonlinear response in the internal dynamics of part of the climate system, qualitatively changing its future state" [*Lenton*, 2011, p. 201]. *Lenton* [2013] noted that the triggering forcing might arise as a result of the level of forcing, the rate of forcing, or system noise.").

[79] Kopp R. E., *et al.* (2017) *Potential surprises – compound extremes and tipping elements*, *in* CLIMATE SCIENCE SPECIAL REPORT: FOURTH NATIONAL CLIMATE ASSESSMENT, VOLUME I ("The second type of surprise arises from self-reinforcing cycles, which can give rise to "tipping elements"—subcomponents of the Earth system that can be stable in multiple different states and can be "tipped" between these states by small changes in forcing, amplified by positive feedbacks. Examples of potential tipping elements include ice sheets, modes of atmosphere–ocean circulation like the El Niño–Southern Oscillation, patterns of ocean circulation like the Atlantic meridional overturning circulation, and large-scale ecosystems like the Amazon rainforest. While compound extremes and tipping elements constitute at least partially "known unknowns," the paleoclimate record also suggests the possibility of "unknown unknowns." These possibilities arise in part from the tendency of current climate models to underestimate past responses to forcing, for reasons that may or may not be explained by current hypotheses (e.g., hypotheses related to positive feedbacks that are unrepresented or poorly represented in existing models).").

[80] Lenton T. (2011) *Early warning of climate tipping points*, NATURE CLIMATE CHANGE 1:201–209, 202 ("The phrase 'tipping point' captures the colloquial notion that 'little things can make a big difference', that is, at a particular moment in time, a small change can have large, long-term consequences for a system. The term 'tipping element' was introduced1 to describe large-scale subsystems (or components) of the Earth system that can be switched — under certain circumstances — into a qualitatively different state by small perturbations. These must be at least sub-continental in scale (length scale of order ~1,000 km). The tipping point is the corresponding critical point — in forcing and a feature of the system — at which the future state of the system is qualitatively altered. …In this definition, the critical threshold (ρ_{crit}) is the tipping point, beyond which a qualitative change occurs, and the

change may occur immediately after the cause or much later."); *see also* Kopp R. E., *et al.* (2016) *Tipping elements and climate–economic shocks: Pathways toward integrated assessment*, EARTH'S FUTURE 4:346–372, 349 ("The difference between committed and realized change is significant from a human perspective for three reasons. First, in some systems, the frictions that lead to a separation of realized and committed change may push the consequences of a tipping point beyond the time horizon of socioeconomic relevance. For example, paleoclimatic evidence from the Last Interglacial period suggests that the committed response to 2 ºC global warming above pre-Industrial era temperatures may be about 6–9 m of GMSL rise [*Kopp et al*., 2009], but if these 6–9 m were to take millennia to be realized, humans and ecosystems might readily adapt to them at minimal cost—in which case they would be of little socioeconomic consequence (in Figure 2g, the rate at which the system shifts states is considerably slower than in Figure 2e). Second, some tipping elements exhibit early warning signs, such as a critical slowing down in the rate of variability and an increase in the magnitude of variability as they approach a critical threshold [*Dakos et al*., 2008; *Scheffer et al*., 2009, 2012; *Lenton*, 2011]. For a forcing that is rapid relative to a system's timescale of variability, whether these warning signs are detectable will relate to the lag between commitment and realization. If there is little or no lag, there will be no opportunity for warning signs. Conversely, if there is a long lag that reflects a generally slow system response time, any early warning signs of a committed state shift may be too slow to identify. Useful early warning signs require both that the speed with which a state shift is realized is slow relative to the system's timescale of variability, so that changes in rate or magnitude of variability have time to manifest before the realized state shift, and also that the timescale of variability be sufficiently fast that such changes are detectable. Third, provided that the committed state shift can be detected, lags between realized and committed changes may allow for interventions, either by reversing the forcing that originally tipped the system or by introducing a different forcing. For example, for some temperature-triggered tipping points, bringing temperatures back down below the tipping point quickly enough—before the previously committed change is fully realized—might avert some or all of that change. Reducing warming rapidly to 0 ºC after peaking at 2.8 ºC might avoid much of the committed sea-level rise, but because of hysteresis, there is no guarantee.").

[81] Lenton T. M., *et al.* (2008) *Tipping elements in the Earth's climate system*, PROC. NAT'L. ACAD. SCI. 105(6):1786–1793, 1786 ("In discussions of global change, the term tipping point has been used to describe a variety of phenomena, including the appearance of a positive feedback, reversible phase transitions, phase transitions with hysteresis effects, and bifurcations where the transition is smooth but the future path of the system depends on the noise at a critical point. We offer a formal definition, introducing the term ''tipping element'' to describe subsystems of the Earth system that are at least subcontinental in scale and can be switched—under certain circumstances— into a qualitatively different state by small perturbations. The tipping point is the corresponding critical point—in forcing and a feature of the system—at which the future state of the system is qualitatively altered."); *see also* Duarte C. M., *et al.* (2012) *Abrupt climate change in the Arctic*, NATURE CLIMATE CHANGE 2:60–62, 60 ("Perhaps the most dangerous aspect of Arctic climate change is the risk of passing tipping points. Tipping points have been defined as critical points, in forcing or some feature of a system, at which a small perturbation can qualitatively alter its future state. Tipping elements are those large-scale components of the Earth system that can exhibit a tipping point. The Arctic region arguably has the greatest concentration of potential tipping elements in the Earth system, including Arctic sea ice, the Greenland ice sheet, North Atlantic deep-water formation regions, boreal forests, permafrost and marine methane hydrates. Recent analyses have added several more candidates."); Overland J. E., *et al.* (2016) *Nonlinear response of mid-latitude weather to the changing Arctic*, NATURE CLIMATE CHANGE 6:992–999, 993 ("Nonlinear relationships are widespread in the Arctic climate system, in which responses are not directly proportional to the change in forcing."); Good P., *et al.* (2016) *Large differences in regional precipitation change between a first and second 2 K of global warming*, NATURE COMMUNICATIONS 7(13667):1–8, 2 ("Nonlinear mechanisms are those inconsistent with linear system theory. These may include state-dependent feedbacks, such as the sea-ice albedo feedback (which vanishes for large or zero sea-ice cover). Nonlinear mechanisms can cause climate patterns to differ at different levels of forcing. For example, if an equivalent of RCP8.5 was run with double the forcing, linear mechanisms would show exactly double the response compared with the standard RCP8.5, but nonlinear mechanisms would not. Nonlinear mechanisms have been demonstrated in a few models for very high-forcing levels, or under idealized CO_2-forced experiments, for global and regional-scale precipitation, warming and ocean heat uptake. In one model study using idealized experiments, nonlinear precipitation change over tropical oceans was associated with interactions between pairs of approximately linear mechanisms (for example, simultaneous moisture increases and circulation shifts). Nonlinear behaviour of the Indian Summer Monsoon associated with the positive moisture advection feedback has also been proposed."); *and* McNeall D., *et al.* (2011) *Analyzing abrupt and nonlinear climate changes and their impacts*, WILEY INTERDISCIPLINARY REVIEWS: CLIMATE CHANGE 2(5):663–686, 663 ("The term 'abrupt change' encompasses a

diverse set of nonlinear system behaviors (one example of which is shown in Figure 1). An abrupt climate change may be defined as where 'the climate system is forced to cross some threshold, triggering a transition to a new state at a rate determined by the climate system itself and is faster than the cause' (Ref 3, p. 14), although other definitions are based on large climate disruptions on decadal or human timescales. A central feature is a qualitative change in how the system operates, when forcing passes beyond some critical threshold or 'tipping point'.").

[82] Lenton T. M., *et al.* (2008) *Tipping elements in the Earth's climate system*, PROC. NAT'L. ACAD. SCI. 105(6):1786–1793, 1792 ("Society may be lulled into a false sense of security by smooth projections of global change. Our synthesis of present knowledge suggests that a variety of tipping elements could reach their critical point within this century under anthropogenic climate change.").

[83] Duarte C. M., *et al.* (2012) *Abrupt climate change in the Arctic*, NATURE CLIMATE CHANGE 2:60–62, 61 ("Several tipping elements have already been set in motion and changes are accelerating.").

[84] Drijfhout S., *et al.* (2015) *Catalogue of abrupt shifts in Intergovernmental Panel on Climate Change climate models*, PROC. NAT'L. ACAD. SCI. 112(43):E5777–E5786, E5777 ("Abrupt transitions of regional climate in response to the gradual rise in atmospheric greenhouse gas concentrations are notoriously difficult to foresee. However, such events could be particularly challenging in view of the capacity required for society and ecosystems to adapt to them. We present, to our knowledge, the first systematic screening of the massive climate model ensemble informing the recent Intergovernmental Panel on Climate Change report, and reveal evidence of 37 forced regional abrupt changes in the ocean, sea ice, snow cover, permafrost, and terrestrial biosphere that arise after a certain global temperature increase. Eighteen out of 37 events occur for global warming levels of less than 2°, a threshold sometimes presented as a safe limit."); *see also* Schellnhuber H. J., *et al.* (2016) *Why the right climate target was agreed in Paris*, NATURE CLIMATE CHANGE 6:649–653, 650 ("[E]ven if global warming is limited to below 2 °C, some important tipping elements may already be harmed or transformed. In fact, the tipping point for marine ice sheet instability in the Amundsen Basin of West Antarctica may well have been crossed already, and the risk of crossing further tipping points will increase with future warming.").

[85] Lontzek T. S., *et al.* (2015) *Stochastic integrated assessment of climate tipping points indicates the need for strict climate policy*, NATURE CLIMATE CHANGE 5:441–444, 441 ("Climate tipping points and their impacts are a key source of uncertainty, for several reasons. First, our knowledge of thresholds, in terms of, for example, regional warming, is imperfect, and the mapping from global temperature rise to regional thresholds is also uncertain. Second, even if we knew a tipping point precisely, stochastic internal variability in the climate system could trigger tipping at a range of times and corresponding global temperatures."); *see also* McNeall D., *et al.* (2011) *Analyzing abrupt and nonlinear climate changes and their impacts*, WILEY INTERDISCIPLINARY REVIEWS: CLIMATE CHANGE 2(5):663–686, 664 ("Some systems may show a move toward an inevitable or 'committed' change in state once a threshold is passed; this may occur abruptly or appear smoothly over a longer timescale, masking the full impacts of the change until well after the threshold is passed. If the system is close to a tipping point, natural variability may be enough to push the system into the new state.").

[86] 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, 10318 ("The Eemian period of 130,000 years ago was an interglacial period similar to the present and was warmer by ~1 °C. It was associated with a 6- to 9-m rise in sea level, which suggests that a warming of 1.5 °C or more sustained over centuries can cause a catastrophic sea level rise."); *see also* Hansen J., *et al.* (2017) *Young people's burden: requirement of negative CO_2 emissions*, EARTH SYSTEMS DYNAMICS 8:577–616, 577 ("We show that global temperature has risen well out of the Holocene range and Earth is now as warm as it was during the prior (Eemian) interglacial period, when sea level reached 6–9 m higher than today. Further, Earth is out of energy balance with present atmospheric composition, implying that more warming is in the pipeline, and we show that the growth rate of greenhouse gas climate forcing has accelerated markedly in the past decade. The rapidity of ice sheet and sea level response to global temperature is difficult to predict, but is dependent on the magnitude of warming."); *and* Committee to Prevent Extreme Climate Change (2017) *Well Under 2 Degrees Celsius: Fast Action Policies to Protect People and the Planet from Extreme Climate Change*, 4 ("In 15 years, planetary warming will reach 1.5°C above pre-industrial global mean temperature (Ramanathan and Xu, 2010; Shindell et al., 2012). This exceeds the 0.5°C to 1°C of warming during the Eemian period, 115,000–130,000 years ago, when sea-levels reached 6–9 meters (20-30 feet) higher than today (Hansen et al., 2016b).").

[87] Kopp R. E., *et al.* (2016) *Tipping elements and climate–economic shocks: Pathways toward integrated assessment*, EARTH'S FUTURE 4:346–372, 349 ("The difference between committed and realized change is significant from a human perspective for three reasons. First, in some systems, the frictions that lead to a separation of realized and committed change may push the consequences of a tipping point beyond the time horizon of

socioeconomic relevance. For example, paleoclimatic evidence from the Last Interglacial period suggests that the committed response to 2ºC global warming above pre-Industrial era temperatures may be about 6–9 m of GMSL rise [*Kopp et al*., 2009], but if these 6–9 m were to take millennia to be realized, humans and ecosystems might readily adapt to them at minimal cost—in which case they would be of little socioeconomic consequence (in Figure 2g, the rate at which the system shifts states is considerably slower than in Figure 2e). Second, some tipping elements exhibit early warning signs, such as a critical slowing down in the rate of variability and an increase in the magnitude of variability as they approach a critical threshold [*Dakos et al*., 2008; *Scheffer et al*., 2009, 2012; *Lenton*, 2011]. For a forcing that is rapid relative to a system's timescale of variability, whether these warning signs are detectable will relate to the lag between commitment and realization. If there is little or no lag, there will be no opportunity for warning signs. Conversely, if there is a long lag that reflects a generally slow system response time, any early warning signs of a committed state shift may be too slow to identify. Useful early warning signs require both that the speed with which a state shift is realized is slow relative to the system's timescale of variability, so that changes in rate or magnitude of variability have time to manifest before the realized state shift, and also that the timescale of variability be sufficiently fast that such changes are detectable.").

[88] Good P., *et al.* (2018) *Recent progress in understanding climate thresholds: Ice sheets, the Atlantic meridional overturning circulation, tropical forests and responses to ocean acidification*, PROGRESS IN PHYSICAL GEOGRAPHY 41(1):24–60, 48 ("For ice sheets and the effects of ocean acidification (combined with warming) on marine ecosystems, it is reasonable to assume that the likelihood of crossing a critical threshold is higher for a 2 ºC world than a 1.5 ºC world. For Greenland, rates of mass loss and SLR are a non-linear function of the temperature increase because of the combined effect of dynamic thinning at the margins and the temperature-elevation feedback (Applegate et al., 2015). A simplified model study of this ice sheet suggested that the global-mean warming threshold for irreversible loss could be only 0.8–3.2 ºC (best estimate 1.6 ºC) above preindustrial levels (Robinson et al., 2012); whereas one long-term coupled model simulation found the threshold of zero surface mass balance may be crossed somewhere between 2 and 3 ºC above pre-industrial levels (Vizcaino et al., 2015).").

[89] 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, 10317–10318 ("The warming probability distribution shown in Fig. 1 (and elsewhere in this paper) is due to the wide range of uncertainties in modeling the climate feedbacks (14). The upper range of warming projection, with a probability of less than 5% (Figs. 1 and 2), may appear unrealistically large, but this may not be the case. Here, we choose to use a high range of climate sensitivity because some studies have suggested that 3D climate models have underestimated three major positive climate feedbacks: positive ice albedo feedback from the retreat of Arctic sea ice (15), positive cloud albedo feedback from retreating storm track clouds in mid- latitudes (16, 17), and positive albedo feedback by the mixed-phase (water and ice) clouds (18) (more discussion is provided in SI Appendix, section 5). The potential underestimation of these feed- backs, along with the positive carbon cycle feedback to be described below, persuaded us to show the warming distribution (Figs. 1 and 2 and SI Appendix) for low probabilities much less than 5%. Again, we caution that we do not use the projected warming with a probability less than 5% for rest of the mitigation analyses.").

[90] McNeall D., *et al.* (2011) *Analyzing abrupt and nonlinear climate changes and their impacts*, WILEY INTERDISCIPLINARY REVIEWS: CLIMATE CHANGE 2(5):663–686, 677 ("Current estimates of the probability of abrupt climate change in the next century under plausible greenhouse gas emissions scenarios are subject to deep structural uncertainty: we might equally characterize them as 'high uncertainty–high impact' events. Recent papers and assessment reports conclude that the most probable of these events are 'very unlikely' (<10% chance) to occur, while with other events even estimating a probability is difficult.").

[91] Cai Y., *et al.* (2016) *Risk of multiple interacting tipping points should encourage rapid CO_2 emission reduction*, NATURE CLIMATE CHANGE 6:520–525, 523–524 ("Putting our results in scientific context, there is already evidence that major ice sheets are losing mass at an accelerating rate. GIS mass loss is estimated to be contributing ~0.7 mm yr^{-1} to sea-level rise, with a corresponding increase in freshwater flux to the North Atlantic since 1990 of ~0.01 Sv. Although modest at present, this and other contributors to increasing freshwater input to the North Atlantic are thought to increase the likelihood of AMOC tipping, and our results suggest that this should be increasing the incentive to control CO_2 emissions. WAIS mass loss is contributing ~0.35mmyr^{-1} to sea-level rise, and there is evidence that parts of the West Antarctic ice sheet are already in irreversible retreat. If the WAIS has already passed a tipping point, then mitigation cannot avoid it, but our results suggest that this should not significantly reduce the incentive to mitigate to try to avoid other tipping events.").

[92] Steffen W., *et al.* (2018) *Trajectories of the Earth System in the Anthropocene*, PROC. NAT'L. ACAD. SCI. 115(33):8252–8259, 8254 ("This risk is represented in Figs. 1 and 2 by a planetary threshold (horizontal broken line

in Fig. 1 on the Hothouse Earth pathway around 2 °C above preindustrial temperature). Beyond this threshold, intrinsic biogeophysical feedbacks in the Earth System (Biogeophysical Feedbacks) could become the dominant processes controlling the system's trajectory. Precisely where a potential planetary threshold might be is uncertain (15, 16). We suggest 2 °C because of the risk that a 2 °C warming could activate important tipping elements (12, 17), raising the temperature further to activate other tipping elements in a domino-like cascade that could take the Earth System to even higher temperatures (Tipping Cascades). Such cascades comprise, in essence, the dynamical process that leads to thresholds in complex systems (section 4.2 in ref. 18).").

[93] Kopp R. E., *et al.* (2016) *Tipping elements and climate–economic shocks: Pathways toward integrated assessment*, EARTH'S FUTURE 4:346–372, 364 ("Climatic tipping elements, climatically sensitive social tipping elements, and climate–economic shocks may all be important contributors to the costs of climate change; indeed, it is possible that they may be the largest contributors. Their incorporation into climate change risk analyses is therefore a crucial task that requires pursuing multiple research pathways.").

[94] Kopp R. E., *et al.* (2016) *Tipping elements and climate–economic shocks: Pathways toward integrated assessment*, EARTH'S FUTURE 4:346–372, 353 ("Both observational and modeling evidence suggests that, if it is a true tipping element, *Arctic sea ice* exhibits Gladwellian behavior. Observations show a significant decrease in sea ice area in response to recent warming, with linear trends of $-54.6 \pm 3.7 \times 10^3$ km^2/year annually and $-89.0 \pm 9.5 \times 10^3$ km^2/year in September between 1978 and 2013 [*Stroeve et al*., 2011, 2012; *Simmonds*, 2015]. Using the ECHAM5/MPI-OM GCM, *Li et al*. [2013] found no lag between changes in the Northern Hemispheric temperature and changes in the Arctic sea ice area. Arctic sea ice also has the potential to be a tipping element, as sea ice loss can be amplified by feedbacks involving ice albedo, the warming effects of convective clouds, the open-water formation efficiency of thin ice, and the increased temperature responsiveness of thinner, younger ice [*Drijfhout et al*., 2015].").

[95] Pistone K., *et al.* (2014) *Observational Determination of Albedo Decrease Caused by Vanishing Arctic Sea Ice*, PROC. NAT'L. ACAD. SCI. 111(9):3322–3326, 3322 ("The Arctic has warmed by nearly 2 °C since the 1970s, a temperature change three times larger than the global mean. During this period, the Arctic sea ice cover has retreated significantly, with the summer minimum sea ice extent decreasing by 40%. This retreat, if not compensated by other changes such as an increase in cloudiness, should lead to a decrease in the Arctic planetary albedo (percent of incident solar radiation reflected to space), because sea ice is much more reflective than open ocean.").

[96] National Snow & Ice Data Center (NSIDC), *Arctic sea ice extent arrives at its minimum* (27 September 2018) ("This year's minimum extent ranked behind 2015 (fifth lowest), 2011 (fourth lowest), 2007 and 2016 (tied for second lowest), and 2012 (lowest). Moreover, the twelve lowest extents in the satellite era have all occurred in the last twelve years.").

[97] Stroeve J. & Notz D. (2018) *Changing state of Arctic sea ice across all seasons*, ENVTL. RESEARCH LETTERS 13(103001):1–23, 9 ("Overall, the proportion of the Arctic Ocean Domain (see figure 4(d)) consisting of perennial ice in April declined from 59% in 1984 to 28% in 2018. The least amount of perennial ice in winter occurred in 2013 (24%), following the 2012 September minimum. While 2018 shows slightly more overall perennial ice than the year before, the amount of perennial ice with an age of 5 years or more was at a minimum (1.9%). For comparison, in 1984 about 28% of the Arctic basin consisted of ice with an age of 5 years or more. The loss of this oldest ice is arguably the most striking change in the sea ice cover within the Arctic Ocean Domain. The proportion of 4 year old ice has also seen a significant decline, dropping from 8.3% of the Arctic Ocean Domain to as low as 1.4% in 2011. Overall, the rate of decline of the 4 year old ice is -27.8% dec^{-1} compared to -50.0% dec^{-1} for the 5+ age class. This has been compensated by an increase in first-year ice at a rate of 16.3% dec^{-1} and in 2nd year ice at a rate of 3.3% dec^{-1}.").

[98] Pistone K., *et al.* (2014) *Observational Determination of Albedo Decrease Caused by Vanishing Arctic Sea Ice*, PROC. NAT'L. ACAD. SCI. 111(9):3322–3326, 3325 ("The change in annual-mean global-mean surface temperature is 0.69 °C during 1979–2011…we find that during 1979–2011 the Arctic darkened sufficiently to cause an increase in solar energy input into the Arctic Ocean region of 6.4 ± 0.9 W/m^2, equivalent to an increase of 0.21 ± 0.03 W/m^2 averaged over the globe. This implies that the albedo forcing due solely to changes in Arctic sea ice has been 25% as large globally as the direct radiative forcing from increased carbon dioxide concentrations, which is estimated to be 0.8 W/m^2 between 1979 and 2011. The present study shows that the planetary darkening effect of the vanishing sea ice represents a substantial climate forcing that is not offset by cloud albedo feedbacks and other processes. Together, these findings provide direct observational validation of the hypothesis of a positive feedback between sea ice cover, planetary albedo, and global warming.").

[99] Arctic Monitoring and Assessment Programme (AMAP) (2017) SNOW, WATER, ICE, AND PERMAFROST IN THE ARCTIC: SUMMARY FOR POLICYMAKERS, 10 ("The Arctic is expected to be largely free of sea ice in late summer

within the next few decades, possibly as early as the 2030s, although natural variability and other factors make it impossible to make precise predictions. The ice that appears in winter will be thinner, more salty, less rigid, and more mobile than today's sea ice."); *see also* Overland J. E. & Wang M. (2013) *When will the summer Arctic be nearly sea ice free?*, GEOPHYSICAL RESEARCH LETTERS 40:2097–2101, 2097 ("The observed rapid loss of thick multiyear sea ice over the last 7years and the September 2012 Arctic sea ice extent reduction of 49% relative to the 1979–2000 climatology are inconsistent with projections of a nearly sea ice-free summer Arctic from model estimates of 2070 and beyond made just a few years ago. 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. It is not possible to clearly choose one approach over another as this depends on the relative weights given to data versus models. 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.").

[100] Jahn A. (2018) *Reduced probability of ice-free summers for 1.5 °C compared to 2 °C warming*, NATURE CLIMATE CHANGE 8:409–413, 409 ("Arctic sea ice has declined rapidly with increasing global temperatures. However, it is largely unknown how Arctic summer sea- ice impacts would vary under the 1.5 °C Paris target compared to scenarios with greater warming. Using the Community Earth System Model, I show that constraining warming to 1.5 °C rather than 2.0 °C reduces the probability of any summer ice-free conditions by 2100 from 100% to 30%. It also reduces the late-century probability of an ice cover below the 2012 record mini- mum from 98% to 55%. For warming above 2 °C, frequent ice-free conditions can be expected, potentially for several months per year. Although sea-ice loss is generally reversible for decreasing temperatures, sea ice will only recover to current conditions if atmospheric CO2 is reduced below present-day concentrations. Due to model biases, these results provide a lower bound on summer sea-ice impacts, but clearly demonstrate the benefits of constraining warming to 1.5 °C."); *and* Sigmond M., *et al.* (2018) *Ice-free Arctic projections under the Paris Agreement*, NATURE CLIMATE CHANGE 8:404–408, 404 ("Under the Paris Agreement, emissions scenarios are pursued that would stabilize the global mean temperature at 1.5–2.0 °C above pre-industrial levels, but current emission reduction policies are expected to limit warming by 2100 to approximately 3.0 °C. Whether such emissions scenarios would prevent a summer sea-ice-free Arctic is unknown. Here we employ stabilized warming simulations with an Earth System Model to obtain sea-ice projections under stabilized global warming, and correct biases in mean sea-ice coverage by constraining with observations. Although there is some sensitivity to details in the con- straining method, the observationally constrained projections suggest that the benefits of going from 2.0 °C to 1.5 °C stabilized warming are substantial; an eightfold decrease in the frequency of ice-free conditions is expected, from once in every five to once in every forty years. Under 3.0 °C global mean warming, however, permanent summer ice-free conditions are likely, which emphasizes the need for nations to increase their commitments to the Paris Agreement.").

[101] Francis J. A. & Vavrus S. J. (2012) *Evidence linking Arctic amplification to extreme weather in mid-latitudes*, GEOPHYSICAL RESEARCH LETTERS 39(L06801):1–6, 1 ("During the past few decades the Arctic has warmed approximately twice as rapidly as has the entire northern hemisphere [Screen and Simmonds, 2010; Serreze et al., 2009], a phenomenon called Arctic Amplification (AA). The widespread warming resulted from a combination of increased greenhouse gases and positive feedbacks involving sea ice, snow, water vapor, and clouds [Stroeve et al., 2012].").

[102] Kopp R. E., *et al.* (2016) *Tipping elements and climate–economic shocks: Pathways toward integrated assessment*, EARTH'S FUTURE 4:346–372, 353 ("Both observational and modeling evidence suggests that, if it is a true tipping element, *Arctic sea ice* exhibits Gladwellian behavior. Observations show a significant decrease in sea ice area in response to recent warming, with linear trends of $-54.6 \pm 3.7 \times 10^3$ km^2/year annually and $-89.0 \pm 9.5 \times 10^3$ km^2/year in September between 1978 and 2013 [*Stroeve et al*., 2011, 2012; *Simmonds*, 2015]. Using the ECHAM5/MPI-OM GCM, *Li et al*. [2013] found no lag between changes in the Northern Hemispheric temperature and changes in the Arctic sea ice area. Arctic sea ice also has the potential to be a tipping element, as sea ice loss can be amplified by feedbacks involving ice albedo, the warming effects of convective clouds, the open-water formation efficiency of thin ice, and the increased temperature responsiveness of thinner, younger ice [*Drijfhout et al*., 2015].").

[103] van Oldenborgh G. J., *et al.*, Climate Central World Weather Attribution, *North Pole, Nov – Dec, 2016* (21 December 2016) "Sixteen climate models with at least three historical simulations (natural and anthropogenic forcings) over 1861–2005, one historicalNat simulation (natural forcings only) for 1861–2005, and one RCP8.5

simulation (projected climate under high greenhouse gas emissions) for 2006–2100, were analysed (see Table 1). Two-month (November and December) temperature anomalies were extracted from all model simulations relative to their own historical 1979–2004 baseline periods. The historical simulations were then compared with ERA-Interim over the 1979–2005 period for their trends and year-to-year variability (Fig. 8). Models with at least one-third of historical simulations having trends greater than double the ERA-Interim linear trend were removed from the analysis leaving the 13 used for subsequent analysis (bold in Table 1). Since the variability in ERA-Interim is close to the average across the CMIP5 simulations, it was not used to remove more models for the analysis described below. However, as a sensitivity test, models with more than one-third of simulations failing either the trend test or with average variability of more than 0.5 ºC (0.9 ºF) above or below the ERA-Interim average were also removed. The results were insensitive to this further restriction on the models. The 13 remaining models (Table 1) were then used to estimate the change in likelihood of events like November-December 2016 or hotter. The likelihoods of such events were estimated in our ensemble of natural runs (for 1901–2005) and the current world runs (2006–2026 in RCP8.5). The temperature anomalies are shown in Fig. 9. Events as hot as 2016 or hotter were not seen in our natural world ensemble. In contrast, events like 2016 or hotter occur in our current world model simulations but are rare, with a return interval of roughly 200 years. These results suggest that it is extremely unlikely this event would occur in the absence of human-induced climate change.").

[104] Overland J., *et al.* (2016) *Surface Air Temperature*, *in* ARCTIC REPORT CARD ("Extreme warm winter and spring air temperatures in 2016 contributed to record low sea ice extents at the beginning of the summer melt season (see essay on *Sea Ice*). But continued record sea ice loss over the summer was not to be. Neutral to cold temperature anomalies (Fig. 1.2d) contrasted to warmer conditions in previous major sea ice loss years (2007, 2012) (Overland et al 2015). The past decade often showed higher sea level pressures (SLP) and warm summer conditions. Summer Arctic 2016 was dominated by low SLP (Fig. 1.4), responsible for two major storms during August. While 2016 is the second lowest summer sea ice extent, the cause contrasted with previous major minimum years; 2016 conditions depended on low initial spring sea ice, rather than supportive summer weather with high SLP, as in recent years.").

[105] Sun L., *et al.* (2018) *Drivers of 2016 record Arctic warmth assessed using climate simulations subjected to Factual and Counterfactual forcing*, WEATHER & CLIMATE EXTREMES 19:1–9, 1 ("Much of the magnitude of surface temperature anomalies averaged poleward of 65ºN in 2016 (3.2 ± 0.6 ºC above a 1980–89 reference) is shown to have been forced by observed global boundary conditions. The Factual experiments reveal that at least three quarters of the magnitude of 2016 annual mean Arctic warmth was forced, with considerable sensitivity to assumptions of sea ice thickness change. Results also indicate that 30–40% of the overall forced Arctic warming signal in 2016 originated from drivers outside of the Arctic. Despite such remote effects, the experiments reveal that the extreme magnitude of the 2016 Arctic warmth could not have occurred without consideration of the Arctic sea ice loss. We find a near-zero probability for Arctic surface temperature to be as warm as occurred in 2016 under late-19th century boundary conditions, and also under 2016 boundary conditions that do not include the depleted Arctic sea ice. Results from the atmospheric model experiments are reconciled with coupled climate model simulations which lead to a conclusion that about 60% of the 2016 Arctic warmth was likely attributable to human-induced climate change.").

[106] Serreze M. C. & Barry R. G. (2011) *Processes and impacts of Arctic amplification: A research synthesis*, GLOBAL PLANET CHANGE 77:85–96 85 ("Viewed in its simplest sense, initial warming will melt some of the Arctic's highly reflective (high albedo) snow and ice cover, exposing darker underlying surfaces that readily absorb solar energy, leading to further warming and further retreat of snow and ice cover."); *see also* World Bank & International Cryosphere Climate Initiative (ICCI) (2013) ON THIN ICE: HOW CUTTING POLLUTION CAN SLOW WARMING AND SAVE LIVES, 13 ("Sea ice is important due to its albedo effect: the broad expanse of sea ice reflects the sun's warmth back into the atmosphere, cooling the entire northern hemisphere. Darker ocean will conversely absorb heat and speed melting in the Arctic (including Greenland and northern permafrost regions) as well as overall global warming. Preserving as much sea ice as possible is therefore important to the global climate system and feedbacks such as sea-level rise and permafrost methane release. The last time the Arctic Ocean was regularly ice-free in summer was 125,000 years ago, during the height of the last major interglacial period (the Eemian). Temperatures in the Arctic today are coming close to those reached during the Eemian maximum, when sea level was 4–6 meters higher because of partial melting on both Greenland and the West Antarctic Ice Sheet (WAIS).").

[107] Marshall J., *et al.* (2014) *The Ocean's Role in Polar Climate Change: Asymmetric Arctic and Antarctic Responses to Greenhouse Gases and Ozone Forcing*, PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY 372:1–17, 2 ("Many mechanisms are at work in 'Arctic amplification' (see, e.g., the overview of and references therein). A positive snow and sea-ice albedo feedback plays a significant role in amplifying the warming signal. The albedo feedback operates in summer when solar radiation is maximal. Where sea ice is lost and water is exposed,

warming due to absorbed shortwave radiation can be large and enhance sea-ice loss through lateral melt. In addition to these processes, the warmed ocean mixed layer delays sea-ice growth, and thus influences wintertime surface temperatures through a thinner ice pack.").

[108] Arctic Council (2016). ARCTIC RESILIENCE REPORT, Carson M. & Peterson G. (eds), Stockholm Environment Institute and Stockholm Resilience Centre, 67–68 ("A regime shift towards ice-free summers is occurring as the Arctic warms, evident from reductions in sea ice surface area and ice volume during the summers. Ice-free summers are expected to occur well within the 21st century (Livina and Lenton 2013). The primary driver behind the shift is warming of the Arctic due to climate change. Several feedback mechanisms have been proposed that may help maintain the reductions in Arctic ice under the new regime (Zhang and Walsh 2006). The primary and best understood is the ice-albedo feedback mechanism: A thick sheet of white ice reflects a large share of the solar radiation that strikes it, while the much darker surface of ocean water absorbs most of the radiation. The radiation, in turn, further warms the water, leading to more sea-ice loss. Thinning ice is also likelier to melt under sunshine, further reducing albedo.").

[109] Vaughan D. G., *et al.* (2013) CHAPTER 4: OBSERVATIONS: CRYOSPHERE, *in* IPCC (2013) CLIMATE CHANGE 2013: THE PHYSICAL SCIENCE BASIS, Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 330 ("The annual Arctic sea ice cover *very likely* declined within the range 3.5 to 4.1% per decade (0.45 to 0.51 million km^2 per decade) during the period 1979–2012 with larger changes occurring in summer and autumn (*very high confidence*). Much larger changes apply to the perennial ice (the summer minimum extent) which *very likely* decreased in the range from 9.4 % to 13.6 % per decade (0.73 to 1.07 million km^2 per decade) and multiyear sea ice (more than 2 years old) which *very likely* declined in the range from 11.0 % to 16.0% per decade (0.66 to 0.98 million km^2 per decade) (*very high confidence*; Figure 4.4b)."); *see also* Pistone K., *et al.* (2014) *Observational Determination of Albedo Decrease Caused by Vanishing Arctic Sea Ice*, PROC. NAT'L. ACAD. SCI. 111(9):3322–3326, 3322 ("The Arctic has warmed by nearly 2 °C since the 1970s, a temperature change three times larger than the global mean. During this period, the Arctic sea ice cover has retreated significantly, with the summer minimum sea ice extent decreasing by 40%. This retreat, if not compensated by other changes such as an increase in cloudiness, should lead to a decrease in the Arctic planetary albedo (percent of incident solar radiation reflected to space), because sea ice is much more reflective than open ocean.").

[110] Pistone K., *et al.* (2014) *Observational Determination of Albedo Decrease Caused by Vanishing Arctic Sea Ice*, PROC. NAT'L. ACAD. SCI. 111(9):3322–3326, 3325 ("We next speculate on the implications of the observed albedo decrease for the climate feedback parameter associated with changes in surface albedo. The change in annual-mean global-mean surface temperature is 0.69 °C during 1979–2011…. Using the relationship between SSM/I and CERES measurements to extend the albedo record back in time, we find that during 1979–2011 the Arctic darkened sufficiently to cause an increase in solar energy input into the Arctic Ocean region of 6.4 ± 0.9 W/m^2, equivalent to an increase of 0.21 ± 0.03 W/m^2 averaged over the globe. This implies that the albedo forcing due solely to changes in Arctic sea ice has been 25% as large globally as the direct radiative forcing from increased carbon dioxide concentrations, which is estimated to be 0.8 W/m^2 between 1979 and 2011.").

[111] Pistone K., *et al.* (2014) *Observational Determination of Albedo Decrease Caused by Vanishing Arctic Sea Ice*, PROC. NAT'L. ACAD. SCI. 111(9):3322–3326, 3325 ("The change in annual-mean global-mean surface temperature is 0.69 °C during 1979–2011…we find that during 1979–2011 the Arctic darkened sufficiently to cause an increase in solar energy input into the Arctic Ocean region of 6.4 ± 0.9 W/m^2, equivalent to an increase of 0.21 ± 0.03 W/m^2 averaged over the globe. This implies that the albedo forcing due solely to changes in Arctic sea ice has been 25% as large globally as the direct radiative forcing from increased carbon dioxide concentrations, which is estimated to be 0.8 W/m^2 between 1979 and 2011. The present study shows that the planetary darkening effect of the vanishing sea ice represents a substantial climate forcing that is not offset by cloud albedo feedbacks and other processes. Together, these findings provide direct observational validation of the hypothesis of a positive feedback between sea ice cover, planetary albedo, and global warming.").

[112] Kim K.-Y., *et al.* (2019) *Vertical Feedback Mechanism of Winter Arctic Amplification and Sea Ice Loss*, SCIENTIFIC REPORTS 9(1184):1–10, 4–5 ("However, the release of turbulent heat flux can continue only when sea surface remains open. While an accurate energy budget is difficult to evaluate in the context of data analysis, Fig. 1a and g indicate that open sea surface area tends to increase in time, leading to increasing turbulent heat flux from the surface in the Barents-Kara Seas (see also Fig. 1e). This indicates that sea ice concentration is not fully recovered every year and turbulent heat flux increases as open sea surface area expands. Heat transport by the warm Norwegian current may be a likely mechanism for keeping the sea surface from freezing. … Therefore, we propose a feedback mechanism as suggested in Fig. 5. Sea ice reduction in this area leads to an increase in upward heat flux,

which is used to raise temperature in the lower troposphere. Warming in the lower troposphere increases downward longwave radiation. As a result, sea ice reduction is accelerated.”).

[113] Kim K.-Y., *et al.* (2019) *Vertical Feedback Mechanism of Winter Arctic Amplification and Sea Ice Loss*, SCIENTIFIC REPORTS 9(1184):1–10, 1 (“Due to the large seasonal variation of insolation, there exists pronounced seasonality in the air-sea interaction process over the Arctic Ocean. During summer, open water readily absorbs solar radiation, which results in increasing heat content in the oceanic mixed layer. This represents the so-called albedo feedback, meaning that the Arctic Ocean is efficient in absorbing atmospheric heat during summer. The albedo feedback is also important during the snow and ice melt in spring and early summer even before the appearance of open sea. After the sun sets over the Arctic Ocean, the ice-albedo feedback is suppressed and the primary air-sea interaction mechanism becomes oceanic horizontal advection and vertical convection of heat. The stored heat in the ocean mixed layer is released back to the colder atmosphere above, which will result in warming of the atmosphere. The decreased insulation effect due to the loss of sea ice also promotes further sea ice reduction. Thus, heat transfer between the ocean and atmosphere is generally considered as the fundamental mechanism of Arctic amplification, which is pronounced only during the cold season. On the other hand, increased cloud cover and water vapor can also contribute to an increase in downward longwave radiation.”).

[114] National Snow & Ice Data Center (NSIDC) *Arctic sea ice maximum ties for seventh lowest in satellite record* (20 March 2019) (“On March 13, 2019, Arctic sea ice likely reached its maximum extent for the year, at 14.78 million square kilometers (5.71 million square miles), the seventh lowest in the 40-year satellite record, tying with 2007. This year’s maximum extent is 860,000 square kilometers (332,000 square miles) below the 1981 to 2010 average maximum of 15.64 million square kilometers (6.04 million square miles) and 370,000 square kilometers (143,000 square miles) above the lowest maximum of 14.41 million square kilometers (5.56 million square miles) set on March 7, 2017. Prior to 2019, the four lowest maximum extents occurred from 2015 to 2018. The date of the maximum this year, March 13, was very close to the 1981 to 2010 median date of March 12.”).

[115] National Snow & Ice Data Center (NSIDC), *Arctic sea ice maximum at second lowest in the satellite record* (23 March 2018) (“The four lowest seasonal maxima have all occurred during the last four years. The 2018 maximum is 60,000 square kilometers (23,200 square miles) above the record low maximum that occurred on March 7, 2017; 40,000 square kilometers (15,400 square miles) below the 2015 and 2016 maxima (now tied for third lowest); and is 190,000 square kilometers (73,400 square miles) below the 2011 maximum, which is now fourth lowest.”).

[116] National Snow & Ice Data Center (NSIDC), *Arctic sea ice extent arrives at its minimum* (27 September 2018) (“On September 19 and 23, 2018, sea ice extent dropped to 4.59 million square kilometers (1.77 million square miles), tying for the sixth lowest minimum in the satellite record along with 2008 and 2010. This appears to be the lowest extent of the year. In response to the setting sun and falling temperatures, ice extent will begin expanding through autumn and winter. However, a shift in wind patterns or a period of late season melt could still push the ice extent lower. … This year’s minimum set on September 23 was 1.20 million square kilometers (463,000 square miles) above the record minimum extent in the satellite era, which occurred on September 17, 2012, and 1.63 million square kilometers (629,000 square miles) below the 1981 to 2010 average minimum extent.”).

[117] National Snow & Ice Data Center (NSIDC), *Arctic sea ice extent arrives at its minimum* (27 September 2018) (“This year’s minimum extent ranked behind 2015 (fifth lowest), 2011 (fourth lowest), 2007 and 2016 (tied for second lowest), and 2012 (lowest). Moreover, the twelve lowest extents in the satellite era have all occurred in the last twelve years.”).

[118] Osborne E., *et al.* (2018) *Executive Summary*, *in* ARCTIC REPORT CARD 2018, 2 (“In 2018, surface air temperatures in the Arctic continued to warm at roughly twice the rate relative to the rest of the globe, a phenomenon that has been termed “Arctic Amplification.” The year 2018 was the second warmest year on record in the Arctic since 1900 (after 2016), at +1.7° C relative to the long- term average (1981–2010). Arctic air temperatures for the past five years (2014–18) have exceeded all previous records since 1900. Growing atmospheric warmth in the Arctic results in a sluggish and unusually wavy jet stream that coincided with abnormal weather events in both the Arctic and mid- latitudes. Notable extreme weather events coincident with deep waves in the jet stream include the heat wave at the North Pole in autumn 2017, a swarm of severe winter storms in the eastern United States in 2018, and the extreme cold outbreak in Europe in March 2018 known as “the Beast from the East.””).

[119] Overland J., *et al.* (2016) *Surface Air Temperature*, *in* ARCTIC REPORT CARD (“The mean annual surface air temperature anomaly (+2.0° C relative to the 1981–2010 mean value) for October 2015–September 2016 for land stations north of 60° N is the highest value in the record starting in 1900 (Fig. 1.1). This is an increase of 3.5° C since the beginning of the 20th Century, and the largest annual increase since 1995. Currently, the Arctic is warming at more than twice the rate of lower latitudes (Fig. 1.1).”).

[120] van Oldenborgh G. J., *et al.*, Climate Central World Weather Attribution, *North Pole, Nov – Dec, 2016* (21 December 2016) ("Mid-November saw an early winter "heat wave" with the temperature on November 11 reaching –7 ºC (19 ºF) – that is 15 ºC (27 ºF) above normal for the time of year. The monthly mean November temperature was 13 ºC (23 ºF) above normal on the pole. Temperatures in this region declined slightly after that but remained well above normal. The forecast for the next few days is again more than 15 ºC (27 ºF) above normal at the North Pole itself and 10 ºC (18 ºF) averaged over 80–90 N."); *see also* WASHINGTON POST, J. Samenow, Pre-Christmas melt? North Pole forecast to warm 50 degrees above normal Thursday (20 December 2016) ("In the middle of the month, the temperature averaged over the entire Arctic north of 80 degrees latitude spiked to 36 degrees above normal.").

[121] National Snow & Ice Data Center, *Sea ice hits record lows* (6 December 2016) ("Through 2016, the linear rate of decline for November is 55,400 square kilometers (21,400 square miles) per year, or 5.0 percent per decade.").

[122] van Oldenborgh G. J., *et al.*, Climate Central World Weather Attribution, *North Pole, Nov – Dec, 2016* (21 December 2016) ("That dip helped November set a record low for sea ice area since 1850 (Walsh et al, 2016). By December, the area around the North Pole is typically 95 percent covered by sea ice. However, this year it is only about 80 percent (Fig. 1b).").

[123] National Snow & Ice Data Center (NSIDC), *A warm approach to the equinox* (6 March 2018) ("Low pressure centered just east of the Kamchatka Peninsula and high pressure centered over Alaska and the Yukon during February set up southerly winds that brought warm air and warm ocean waters into the Pacific side of the Arctic Ocean, impeding southward ice growth. This helps to explain the rapid loss of ice extent in the Bering Sea and the ice-free regions within the Chukchi Sea during the month. The warm air intrusion is evident in the 925 mb air temperatures, with monthly temperatures 10 to 12 degrees Celsius (18 to 22 degrees Fahrenheit) above average in the Chukchi and Bering Sea.").

[124] National Snow & Ice Data Center (NSIDC), *A warm approach to the equinox* (6 March 2018) ("On the Atlantic side, low pressure off the southeast coast of Greenland and high pressure over northern Eurasia helped to funnel warm winds into the region and may have also enhanced the northward transport of oceanic heat. At the end of the month, this atmospheric circulation pattern was particularly strong, associated with a remarkable inflow of warm air from the south, raising the temperatures near the North Pole to above freezing, around 20 to 30 degrees Celsius (36 to 54 degrees Fahrenheit) above average. Air temperatures at Cape Morris Jesup in northern Greenland (83°37'N, 33°22'W) exceeded 0 degrees Celsius for several hours and open water formed to the north of Greenland at the end of the month. This is the third winter in a row in which extreme heat waves have been recorded over the Arctic Ocean. A study published last year by Robert Graham from the Norwegian Polar Institute showed that recent warm winters represent a trend towards increased duration and intensity of winter warming events within the central Arctic. While the Arctic has been relatively warm for this time of year, northern Europe was hit by extreme cold conditions at the end of February.").

[125] National Snow & Ice Data Center (NSIDC), *Arctic winter warms up to a low summer ice season* (3 May 2018) ("On February 24, during the peak of the polynya opening, air temperatures at Cape Morris Jesup, Greenland's northernmost station, surged well above freezing, reaching 6.1 degrees Celsius (43 degrees Fahrenheit), while the daily average temperature hovered just above freezing (Figure 6b). Such periods of extremely warm winter temperatures have been unusual since the beginning of the Cape Morris Jesup record in 1981. During the month of February, only a few years exhibited hourly air temperatures rising above 0 degrees Celsius (32 degrees Fahrenheit): once in 1997, five times in 2011, seven in 2017 and 59 times in 2018.").

[126] National Snow & Ice Data Center (NSIDC), *A warm approach to the equinox* (6 March 2018) ("The Arctic Ocean is becoming more accessible for shipping. Most of the increase in commercial shipping traffic has been during summer, primarily through the Northern Sea Route along the coast of Siberia. However, this February a commercial tanker, the *Eduard Toll*, made the first crossing of the Northern Sea Route in winter. Improvements in ship-building and the development of ice-strengthened hull technology is a major factor in enabling winter access. Previous ice-strengthened ships could only navigate safely through 0.5 meter thick ice, compared to the 1.8 meter thick ice that the *Eduard Toll* cruised through. A fleet of six ships with similar technology is being constructed by a South Korean shipbuilder. While the Northern Sea Route has tended to be dominated by first-year ice, which typically reaches a maximum of around 2 meters, thicker (3- to 4-meter) multi-year ice would be a hazard even to the newer, stronger ships. According to analysis by the U.S. National Ice Center, this year's old ice (multi-year ice) has pulled completely away from the coast and the Northern Sea Route is dominated by first-year medium (0.7- to 1.2-meter) or first-year thick (1.2- to 2-meter) ice."); *see* also THE GUARDIAN, M. Darby, *Shipping first as commercial tanker crosses Arctic sea route in winter* (13 February 2018) ("An LNG tanker designed for icy conditions has become the first commercial ship to travel the Arctic's northern sea route in winter. It marks a

milestone in the opening up of Russia's northern coastline, as thawing polar ice makes industrial development and maritime trade increasingly viable. The Teekay vessel Eduard Toll set out from South Korea in December for Sabetta terminal in northern Russia, cutting through ice 1.8m thick. Last month, it completed the route, delivering a load of liquefied natural gas (LNG) to Montoir, France.").

[127] Stroeve J. & Notz D. (2018) *Changing state of Arctic sea ice across all seasons*, ENVTL. RESEARCH LETTERS 13(103001):1–23, 18 ("Finally, the loss of the summer sea ice cover opens up the potential for increased shipping activities, new fisheries and new locations for resource extraction. Regarding shipping, Smith and Stephenson (2013) find that the Northern Sea Route becomes navigable for both the RCP4.5 and the RCP8.5 emission scenarios by mid-century. While internal variability will continue to substantially affect the ease of transit from one year to the next, in terms of long-term planning the future emission pathways are the main source of uncertainty. For example, Melia et al (2016) find that by the end of the century, the possible shipping period reaches a duration of 4 to 8 months in the high emission RCP8.5 scenario, while it is just about half that long for the low-emission scenario RCP2.6. Other estimates project 5 months of ice free conditions along the Northern Sea Route by the end of this century under RCP8.5, using both SIC and ice thickness constraints (Bensassi et al 2015). In practice, the future use of these shipping routes will substantially depend on the economic and geopolitical boundary conditions (e.g., Ho 2010, Schøyen and Bråthen 2011, Bensassi et al 2015) and on the type of ship used for the transit (Smith and Stephenson 2013, Melia et al 2016).").

[128] Stroeve J. & Notz D. (2018) *Changing state of Arctic sea ice across all seasons*, ENVTL. RESEARCH LETTERS 13(103001):1–23, 9 ("Overall, the proportion of the Arctic Ocean Domain (see figure 4(d)) consisting of perennial ice in April declined from 59% in 1984 to 28% in 2018. The least amount of perennial ice in winter occurred in 2013 (24%), following the 2012 September minimum. While 2018 shows slightly more overall perennial ice than the year before, the amount of perennial ice with an age of 5 years or more was at a minimum (1.9%). For comparison, in 1984 about 28% of the Arctic basin consisted of ice with an age of 5 years or more. The loss of this oldest ice is arguably the most striking change in the sea ice cover within the Arctic Ocean Domain. The proportion of 4 year old ice has also seen a significant decline, dropping from 8.3% of the Arctic Ocean Domain to as low as 1.4% in 2011. Overall, the rate of decline of the 4 year old ice is −27.8% dec^{-1} compared to −50.0% dec^{-1} for the 5+ age class. This has been compensated by an increase in first-year ice at a rate of 16.3% dec^{-1} and in 2nd year ice at a rate of 3.3% dec^{-1}.").

[129] Arctic Monitoring and Assessment Programme (AMAP) (2017) SNOW, WATER, ICE, AND PERMAFROST IN THE ARCTIC: SUMMARY FOR POLICYMAKERS, 4 ("Sea ice thickness in the central Arctic Ocean declined by 65% over the period 1975–2012. Sea ice extent has varied widely in recent years, but continues a long-term downward trend. A record low minimum sea ice extent occurred in 2012 and a record low maximum sea ice extent occurred in 2016. Older ice that has survived multiple summers is rapidly disappearing; most sea ice in the Arctic is now 'first year' ice that grows in the autumn and winter but melts during the spring and summer."); *see also* Perovich D., Meier W., Tschudi M., Farrell S., Hendricks S., Gerland S., Haas C., Krumpen T., Polashenski C., Ricker R., & Webster M. (2017) *Sea Ice*, *in* ARCTIC REPORT CARD 2017 ("The CryoSat-2 sea-ice volume estimates (Fig. 5) for the central Arctic Ocean showed a continued decline from 2014 through 2017. The April 2017 sea-ice volume of 13.19 ± 1.15 thousand cubic kilometers ranks as the third lowest spring volume after April 2012 (13.14 ±1.27) and 2013 (12.56 ± 1.21) in the AWI CryoSat-2 data record. The difference between the three lowest volume estimates lies within the observational uncertainties."); *see also* News Release, National Oceanic and Atmospheric Administration (NOAA), *Arctic saw 2nd warmest year, smallest winter sea ice coverage on record in 2017* (12 December 2017) ("Declining sea ice. This year's maximum winter sea ice area, measured each March, was the lowest ever observed, while this year's minimum area, measured each September, was eighth-lowest on record. Sea ice is also getting thinner each year, with year-old ice comprising 79 percent of coverage, and multi-year ice just 21 percent. In 1985, multi-year ice accounted for 45 percent of sea ice.").

[130] Arctic Monitoring and Assessment Programme (AMAP) (2017) SNOW, WATER, ICE, AND PERMAFROST IN THE ARCTIC: SUMMARY FOR POLICYMAKERS, 8 ("Sea ice in the Arctic is entering a new regime in which vast areas of ocean that used to be covered by ice throughout the year are now seasonally ice-free and dominated by younger, thinner ice.").

[131] Perovich D., *et al.* (2018) *Sea Ice*, *in* ARCTIC REPORT CARD 2018, 28 ("Older ice tends to be thicker and is thus more resilient to changes in atmospheric and oceanic heat content compared to younger, thinner ice. The oldest ice (>4 years old) continues to make up a small fraction of the Arctic ice pack in March, when the sea ice extent has been at its maximum in most years of the satellite record. In 1985, the oldest ice comprised 16% of the ice pack (Fig. 3a), whereas in March of 2018 old ice only constituted 0.9% of the ice pack (Fig. 3b). Therefore, the oldest ice

extent declined from 2.54 million km^2 in March 1985 to 0.13 million km^2 in March 2018, representing a 95% reduction.").

[132] Duarte C. M., *et al.* (2012) *Abrupt climate change in the Arctic*, NATURE CLIMATE CHANGE 2:60–62, 61 ("The fact that sea ice has almost recovered to its full areal extent in the winters following recent minima does not imply that the ice loss has been fully reversed. The thickness of the ice cannot be rebuilt over one winter following summer minima. Indeed, the sensitivity of Arctic sea ice to climate warming depends on the thickness of the ice. Although records of Arctic sea-ice thickness are far less robust than those of its areal extent, they show unambiguously that Arctic sea-ice volume has declined dramatically over the past two decades. Most of the sea-ice area present in the spring now represents first-year ice, prone to melting during summer.").

[133] Stroeve J. & Notz D. (2018) *Changing state of Arctic sea ice across all seasons*, ENVTL. RESEARCH LETTERS 13(103001):1–23, 13 ("Bathiany et al (2016) explain this behavior by a simple geometric argument: The loss of summer sea ice proceeds comparably slowly, because the ice thickness distribution is rather broad and in a given summer, the thinnest ice disappears while thicker ice might stay behind. For the loss of winter sea ice, however, the distribution in ice thickness will be much narrower, as only first-year ice will be left behind. Once temperatures have risen enough to prevent ice formation during winter, the Arctic Ocean can rapidly change from an ocean largely ice covered in winter to an ocean that remains ice free throughout winter.").

[134] Richter-Menge J., *et al.* (2016) *Executive Summary*, *in* ARCTIC REPORT CARD ("In March 2016, multiyear ice (more than 1 year old) and first-year ice were 22% and 78% of the ice cover, respectively, compared to 45%s and 55% in 1985.").

[135] Perovich D., Meier W., Tschudi M., Farrell S., Hendricks S., Gerland S., Haas C., Krumpen T., Polashenski C., Ricker R., & Webster M. (2017) *Sea Ice*, *in* ARCTIC REPORT CARD 2017 ("Very old ice (>4 years old) continues to make up a small fraction of the Arctic ice pack in March, when the sea ice extent is at its maximum (Fig. 3). In 1985, 16% of the ice pack was very old ice, but by March 2017, this ice category only constituted 0.9% of the ice pack. The extent of the oldest ice declined from 2.54 million km^2 in March 1985 to 0.13 million km^2 in March 2017. The distribution of ice age in March 2017 was similar to that in March of the previous year, although there was a decrease in the oldest ice fractional coverage, from 1.2% in March 2016 to 0.9% in March 2017.").

[136] Osborne E., *et al.* (2018) *Executive Summary*, *in* ARCTIC REPORT CARD 2018, 2 ("The disappearance of the older and thicker classes of sea ice are leaving an ice pack that is more vulnerable to melting in the summer, and liable to move unpredictably. When scientists began measuring Arctic ice thickness in 1985, 16% of the ice pack was very old (i.e., multiyear) ice. In 2018, old ice constituted less than 1% of the ice pack, meaning that very old Arctic ice has declined by 95% in the last 33 years. The pace and extent of the changes to summer sea ice cover, along with regional air temperatures and advection of waters from the Pacific and Atlantic oceans, are linked to the spatial patterns of late summer sea surface temperature. August mean sea surface temperatures in 2018 show statistically significant warming trends for 1982–2018 in most regions of the Arctic Ocean that are ice-free in August.").

[137] An "ice-free" Arctic does not mean that the Arctic is completely devoid of ice; rather, the agreed upon definition is 1 million square kilometers of ice is considered "ice-free". *See* Overland J. E. & Wang M. (2013) *When will the summer Arctic be nearly sea ice free?*, GEOPHYSICAL RESEARCH LETTERS 40:2097–2101, 2097 ("[T]he practical limit for sea ice loss is arbitrary, but several sources have converged on 1.0 M km^2 as a minimum transition point.").

[138] Arctic Monitoring and Assessment Programme (AMAP) (2017) SNOW, WATER, ICE, AND PERMAFROST IN THE ARCTIC: SUMMARY FOR POLICYMAKERS, 10 ("The Arctic is expected to be largely free of sea ice in late summer within the next few decades, possibly as early as the 2030s, although natural variability and other factors make it impossible to make precise predictions. The ice that appears in winter will be thinner, more salty, less rigid, and more mobile than today's sea ice.").

[139] Overland J. E. & Wang M. (2013) *When will the summer Arctic be nearly sea ice free?*, GEOPHYSICAL RESEARCH LETTERS 40:2097–2101, 2098 ("While the PIOMAS team does not directly extrapolate, the already major volume loss of 70%–80% and recent losses suggest that extrapolation into the future from the current volume amount shows that Arctic sea ice is vulnerable within the next decade.").

[140] Overland J. E. & Wang M. (2013) *When will the summer Arctic be nearly sea ice free?*, GEOPHYSICAL RESEARCH LETTERS 40:2097–2101, 2099 ("The key argument of the stochasters is that it will take several rapid loss events such as that which occurred in 2007 and 2012 to reach the 1.0 M km^2 sea ice extent threshold. If we select the 5 year interval that occurred between the 2007 and 2012 sea ice loss events as an expected value, then three more events puts a nearly sea ice-free timing at 2028. …[T]he stochasters would require 20 years or more after 2007 or around 2030 with a wide range of uncertainty to have several rapid ice loss events occur and to reach nearly sea ice-free conditions. While not unreasonable, stochasters are the most ad hoc of the three approaches.").

[141] Overland J. E. & Wang M. (2013) *When will the summer Arctic be nearly sea ice free?*, GEOPHYSICAL RESEARCH LETTERS 40:2097–2101, 2100 ("There are four major evaluations of sea ice projections in the set of CMIP5 GCMs…. The median value for each year of all available CMIP5 ensemble members…reaches the nearly sea ice-free condition near 2060 based on a nearly sea ice-free definition of 1.0 M km^2. However, given the large observed rate of sea ice loss, we are primarily interested in model ensemble members with the most rapid sea ice loss. … Several of the ensemble members of CCSM4 reach the sea ice loss threshold near 2060; this was 10 years later than their previous model CCSM3.The EC-Earth model also becomes nearly sea ice free near 2060, but the authors suggest shifting this to 2040 based on the model's overestimate of the amount of sea ice in the twentieth century. Thus, we put the early limit for sea ice loss based on GCM projections near 2040."); *see also* Overland J. E., *et al.* (2014) *Future Arctic climate changes: Adaptation and mitigation time scales*, EARTH'S FUTURE 2:68–74, 70 ("CMIP5 projections are subject to three main types of uncertainty: model differences, internal variability, and choice of emission scenario [*Overland et al*., 2011; *Hodson et al*., 2012]. Model variations are due to different formulations and parameterization of physical processes; internal variability arises from the chaotic nature of the earth's climate system and leads to different results for similar initial conditions of the models. Near-term projections are dominated by these two types of uncertainties.").

[142] Sanderson B. M., *et al.* (2017) *Community climate simulations to assess avoided impacts in 1.5 and 2 ºC futures*, EARTH SYSTEM DYNAMICS 8:827–847, 831 ("Ice-free is defined as a condition where September average Arctic sea-ice area is less than 1 million square kilometers. Our analysis counts the number of ice-free September years in a 20-year moving window in each 10-member ensemble to assess the probability of ice-free conditions as a function of time. We find that in 1.5degNE, ice-free conditions remain rare, a 1-in-40-year occurrence by the end of the century. In 1.5degOS, the likelihood of ice-free conditions peaks in 2060, where there is a 1 in 15 chance of ice-free conditions – but this likelihood then declines such that the likelihood is similar to 1.5degNE by 2100. However, the 2.0degNE shows significantly greater chances of ice-free conditions; by 2100, 1 in 3 years is simulated as ice-free with likelihoods still increasing at the end of the century. It is notable that the difference between the 2.0 and 1.5 ºC scenarios largely arises due to the reduced summer survival of multi-year ice in 2.0degNE, with only 8 % of annual mean sea ice in 2100 in 2.0degNE that is older than 1 year, compared with 15–20 % in the 1.5degNE and 1.5degOS (and 35 % in 2005 – see Fig. C2 in the Appendix). Compared to recent statistical analysis of CMIP5 RCP8.5 and RCP4.5 simulations by Screen and Williamson (2017), our results show a higher likelihood of ice-free conditions for 1.5degOS."); *see also* Jahn A. (2018) *Reduced probability of ice-free summers for 1.5 °C compared to 2 °C warming*, NATURE CLIMATE CHANGE 8:409–413, 409 ("Arctic sea ice has declined rapidly with increasing global temperatures. However, it is largely unknown how Arctic summer sea-ice impacts would vary under the 1.5 °C Paris target compared to scenarios with greater warming. Using the Community Earth System Model, I show that constraining warming to 1.5 °C rather than 2.0 °C reduces the probability of any summer ice-free conditions by 2100 from 100% to 30%. It also reduces the late-century probability of an ice cover below the 2012 record minimum from 98% to 55%. For warming above 2 °C, frequent ice-free conditions can be expected, potentially for several months per year. Although sea-ice loss is generally reversible for decreasing temperatures, sea ice will only recover to current conditions if atmospheric CO_2 is reduced below present-day concentrations. Due to model biases, these results provide a lower bound on summer sea-ice impacts, but clearly demonstrate the benefits of constraining warming to 1.5 °C."); *and* Sigmond M., *et al.* (2018) *Ice-free Arctic projections under the Paris Agreement*, NATURE CLIMATE CHANGE 8:404–408, 404 ("Under the Paris Agreement, emissions scenarios are pursued that would stabilize the global mean temperature at 1.5–2.0 °C above pre-industrial levels, but current emission reduction policies are expected to limit warming by 2100 to approximately 3.0 °C. Whether such emissions scenarios would prevent a summer sea-ice-free Arctic is unknown. Here we employ stabilized warming simulations with an Earth System Model to obtain sea-ice projections under stabilized global warming, and correct biases in mean sea-ice coverage by constraining with observations. Although there is some sensitivity to details in the constraining method, the observationally constrained projections suggest that the benefits of going from 2.0 °C to 1.5 °C stabilized warming are substantial; an eightfold decrease in the frequency of ice-free conditions is expected, from once in every five to once in every forty years. Under 3.0 °C global mean warming, however, permanent summer ice-free conditions are likely, which emphasizes the need for nations to increase their commitments to the Paris Agreement.").

[143] Sanderson B. M., *et al.* (2017) *Community climate simulations to assess avoided impacts in 1.5 and 2 ºC futures*, EARTH SYSTEM DYNAMICS 8:827–847, 827 ("Exceedance of historical record temperature occurs with 60 % greater frequency in the 2 ºC climate than in a 1.5 ºC climate aggregated globally, and with twice the frequency in equatorial and arid regions. Extreme precipitation intensity is statistically significantly higher in a 2.0 ºC climate than a 1.5 ºC climate in some specific regions (but not all). The model exhibits large differences in the Arctic, which

is ice-free with a frequency of 1 in 3 years in the 2.0 ºC scenario, and 1 in 40 years in the 1.5 ºC scenario. Significance of impact differences with respect to multi-model variability is not assessed."); *see also* Screen J. A. & Williamson D. (2017) *Ice-free Arctic at 1.5ºC?*, NATURE CLIMATE CHANGE 7:230–231, 230 ("Using Bayesian statistics allows us to compare estimates of the probability of an ice-free Arctic for the 1.5 °C or 2 °C target (Fig. 1c). We estimate there is less than a 1-in-100,000 (exceptionally unlikely, in IPCC parlance) chance of an ice-free Arctic if global warming stays below 1.5 °C, and around a 1-in-3 chance (39%; about as likely as not, in IPCC parlance) if global warming is limited to 2.0 °C. We suppose then that a summer ice-free Arctic is virtually certain to be avoided if the 1.5 °C target of the Paris Agreement is met. However, the 2 °C target may be insufficient to prevent an ice-free Arctic."); *and* Jahn A. (2018) *Reduced probability of ice-free summers for 1.5 °C compared to 2 °C warming*, NATURE CLIMATE CHANGE 8:409–413, 409 ("Using the Community Earth System Model, I show that constraining warming to 1.5 °C rather than 2.0 °C reduces the probability of any summer ice-free conditions by 2100 from 100% to 30%. It also reduces the late-century probability of an ice cover below the 2012 record minimum from 98% to 55%. For warming above 2 °C, frequent ice-free conditions can be expected, potentially for several months per year.").

[144] Sigmond M., *et al.* (2018) *Ice-free Arctic projections under the Paris Agreement*, NATURE CLIMATE CHANGE 8:404–408, 405 ("Prior to reaching 1.5 °C, 2.0 °C and 3.0 °C of global warming, the probability of having reached an ice-free Arctic at least once is 10%, 80% and 100%, respectively. We emphasize that these ice-free probabilities derived from transient warming runs only apply to the period before reaching the temperature targets.").

[145] Jahn A. (2018) *Reduced probability of ice-free summers for 1.5 °C compared to 2 °C warming*, NATURE CLIMATE CHANGE 8:409–413, 411 ("However, in the low-warming scenarios, it is likely to be an isolated event, whereas in the stronger-warming scenarios a second ice-free year would soon follow the first (Supplementary Section 1 and Supplementary Fig. 3d). The largest impact of scenario differences on the timing of the first possible occurrence of an ice-free Arctic in September is again found for limiting warming to 1.5°C rather than 2.0°C (Fig. 3a). This means that limiting warming to 1.5 °C is likely to delay ice-free conditions in September, and could avoid them altogether.").

[146] Sanderson B. M., *et al.* (2017) *Community climate simulations to assess avoided impacts in 1.5 and 2 ºC futures*, EARTH SYSTEM DYNAMICS 8:827–847, 828 ("For the lower Paris Agreement temperature goal of 1.5ºC, coherent efforts beginning in 2017 would require both emissions rate reductions of at least 5 % yr^{-1} (Sanderson et al., 2016) and likely substantial commitment to negative net carbon emission technologies in the second half of the century (Smith et al., 2016).").

[147] Sigmond M., *et al.* (2018) *Ice-free Arctic projections under the Paris Agreement*, NATURE CLIMATE CHANGE 8:404–408, 405 ("Despite delayed ocean warming after stabilization (not shown), the SSIE stabilizes as soon as the global mean temperature has stabilized. However, the accumulated ice-free probability (Fig. 2c) does not stabilize. Instead, it rapidly increases from 14% at the first crossing of the 1.5 °C threshold (indicated by the circle) to 98% about 25 years later, and reaches 100% two decades thereafter. In other words, even though only a small fraction of ensemble members reach ice-free conditions at the time of the first crossing of the 1.5 °C global warming threshold, less than half-a-century later all the ensemble members have reached ice-free conditions at least once. For the 2.0 °C ensemble the accumulated ice-free probability reaches 100% less than a decade after the temperature threshold is first exceeded. The accumulated ice-free probability continues to increase, even after the ensemble mean SSIE has stabilized, because more phases of random internal variability are sampled as time goes on.").

[148] Jahn A., *et al.* (2016) *How predictable is the timing of a summer ice-free Arctic?*, GEOPHYSICAL RESEARCH LETTERS 43:9113–9120, 9113 ("Based on results from large ensemble simulations with the Community Earth System Model, we show that internal variability alone leads to a prediction uncertainty of about two decades, while scenario uncertainty between the strong (Representative Concentration Pathway (RCP) 8.5) and medium (RCP4.5) forcing scenarios adds at least another 5 years. Common metrics of the past and present mean sea ice state (such as ice extent, volume, and thickness) as well as global mean temperatures do not allow a reduction of the prediction uncertainty from internal variability.").

[149] The Representative Concentration Pathways are referenced extensively within climate change literature. These four scenarios were developed prior to the IPCC Fifth Assessment Report (AR5) and cover a range of possibilities for future climates based on radiative forcing achieved at 2100. RCP8.5 represents forcing of 8.5 W/m^2 and is the akin to business-as-usual while also the highest radiative forcing of the scenarios. The lowest forcing is RCP2.6, with RCP4.5 and RCP6.0 making up the middle ground. van Vuuren D. P., *et al.* (2011) *The representative concentration pathways: an overview*, CLIMATIC CHANGE 109:5–31, 5 ("This paper summarizes the development process and main characteristics of the Representative Concentration Pathways (RCPs), a set of four new pathways developed for the climate modeling community as a basis for long-term and near-term modeling experiments. The

four RCPs together span the range of year 2100 radiative forcing values found in the open literature, i.e. from 2.6 to 8.5 W/m^2. The RCPs are the product of an innovative collaboration between integrated assessment modelers, climate modelers, terrestrial ecosystem modelers and emission inventory experts. The resulting product forms a comprehensive data set with high spatial and sectoral resolutions for the period extending to 2100. Land use and emissions of air pollutants and greenhouse gases are reported mostly at a 0.5 × 0.5 degree spatial resolution, with air pollutants also provided per sector (for well-mixed gases, a coarser resolution is used). The underlying integrated assessment model outputs for land use, atmospheric emissions and concentration data were harmonized across models and scenarios to ensure consistency with historical observations while preserving individual scenario trends. For most variables, the RCPs cover a wide range of the existing literature. The RCPs are supplemented with extensions (Extended Concentration Pathways, ECPs), which allow climate modeling experiments through the year 2300. The RCPs are an important development in climate research and provide a potential foundation for further research and assessment, including emissions mitigation and impact analysis.").

[150] Jahn A., *et al.* (2016) *How predictable is the timing of a summer ice-free Arctic?*, GEOPHYSICAL RESEARCH LETTERS 43:9113–9120, 9114 ("Internal variability leads to a substantial spread in the ensemble simulations of the September sea ice extent in the CESM LE and ME simulations (Figures 1a and 1b). The range of dates when each ensemble member's monthly mean September sea ice extent reaches (or crosses) the 1 million km^2 "ice-free" threshold for the first time is 2032–2053 under the strong forcing scenario used in the CESM LE and 2043–2058 under the medium forcing scenario used in the CESM ME (Figure 1c). This means that due to internal variability alone, the timing of an ice-free summer Arctic has a prediction uncertainty of up to 21 years.").

[151] Jahn A. (2018) *Reduced probability of ice-free summers for 1.5 °C compared to 2 °C warming*, NATURE CLIMATE CHANGE 8:409–413, 410 ("The timing of the first possible occurrence of an ice-free Arctic in September is strongly impacted by internal variability. …This is due to an enhanced internal variability in the low-warming scenarios, as their mid-century September SIEs are close to the peak of the ice-extent standard deviation (around 3.5 million km^2 and 1.4 °C global mean warming (Supplementary Fig. 5)). This enhanced internal variability leads to the first ice-free conditions occurring at global temperature anomalies as low as 1.4 °C in one of the 1.5 °C ensemble members (Fig. 3b), even though the CESM ensemble mean temperature at which ice-free conditions occur for the first time is 1.9 °C.").

[152] Jahn A. (2018) *Reduced probability of ice-free summers for 1.5 °C compared to 2 °C warming*, NATURE CLIMATE CHANGE 8:409–413, 409 ("Even when warming is limited to 1.5 °C, the Arctic summer sea-ice cover experiences significant reductions compared to today's cover. By the end of the twenty-first century, 55% of the September SIEs are below the record minimum to date (in 2012, Fig. 1a). However, if warming reaches 2.0 °C, 98% of September SIEs will be below the record 2012 minimum by the late twenty-first century (Fig. 1a). For an even larger warming, the late twenty-first century Arctic sea-ice cover will be in a completely different regime to that known so far, with September SIEs far below those observed over the past 38 years and a high probability of ice-free conditions (Fig. 1a).").

[153] Stroeve J. & Notz D. (2018) *Changing state of Arctic sea ice across all seasons*, ENVTL. RESEARCH LETTERS 13(103001):1–23, 2 ("While complete loss of the summer sea-ice cover will have far-reaching implications beyond the Arctic, the observed reductions in sea-ice thickness and coverage are already impacting the energy balance of our planet. Expanding open water areas during summer have allowed for more absorption of heat into the ocean mixed layer, warming ocean temperatures and delaying autumn freeze-up (Stroeve et al 2014a). Before the ice can form again in winter, the ocean must release this heat back to the atmosphere. Large exchanges of heat and moisture from the ocean to the atmosphere have thus contributed to amplified winter warming of the lower troposphere in the Arctic (e.g. Serreze et al 2009), increased atmospheric moisture content of the Arctic atmosphere (Serreze et al 2012, Boivsert and Stroeve 2015), increased cloud cover (e.g. Jun et al 2016) and increased autumn precipitation (e.g. Kopec et al 2016). Warming from sea-ice loss has additionally been shown to impact permafrost temperatures (Lawrence et al 2008) and may have local impacts on Greenland melt (Stroeve et al 2017).").

[154] Stroeve J. & Notz D. (2018) *Changing state of Arctic sea ice across all seasons*, ENVTL. RESEARCH LETTERS 13(103001):1–23, 10 ("As the ice cover thins, the same amount of heat input can cause larger expanses of open water (e.g., Holland et al 2006, Maslanik 2007, Notz 2009). To more robustly assess if this has caused an increase in RILEs during summer, we examined the change in Arctic SIE over all 7 day long periods from November 1978 until today (figure 6). We define two different thresholds for RILEs, namely the loss of at least 800 000 (blue) or of at least 1 million km^2 (red) of SIE within 7 d. We find that for both thresholds, the frequency of RILEs has substantially increased since 2005. Indeed, the first RILE with an ice loss of more than 1 million km^2 only occurred in early July 2007, with similar events in early July 2014 and 2015. In 2012, the great cyclone during August

resulted in a little less than 900 000 km^2 of ice loss over a 7 day period. The largest amount of ice loss during any single week-long period occurred in early July 2007, with a total ice loss of nearly 1.2 million km^2.").

[155] Lawrence D. M., *et al.* (2008) *Accelerated Arctic land warming and permafrost degradation during rapid sea ice loss*, GEOPHYSICAL RESEARCH LETTERS 35(L11506):1–6, 5 ("We find that rapid sea ice loss forces a strong acceleration of Arctic land warming in CCSM3 (3.5-fold increase, peaking in autumn) which can trigger rapid degradation of currently warm permafrost and may increase the vulnerability of colder permafrost for subsequent degradation under continued warming. Our results also suggest that talik formation may be a harbinger of rapid subsequent terrestrial change. This sea ice loss – land warming relationship may be immediately relevant given the record low sea ice extent in 2007.").

[156] Kim B.-M., *et al.* (2017) *Major cause of unprecedented Arctic warming in January 2016: Critical role of an Atlantic windstorm*, SCIENTIFIC REPORTS 7(40051):1–9, 1 ("In January 2016, the Arctic experienced an extremely anomalous warming event after an extraordinary increase in air temperature at the end of 2015. During this event, a strong intrusion of warm and moist air and an increase in downward longwave radiation, as well as a loss of sea ice in the Barents and Kara seas, were observed. Observational analyses revealed that the abrupt warming was triggered by the entry of a strong Atlantic windstorm into the Arctic in late December 2015, which brought enormous moist and warm air masses to the Arctic. Although the storm terminated at the eastern coast of Greenland in late December, it was followed by a prolonged blocking period in early 2016 that sustained the extreme Arctic warming. Numerical experiments indicate that the warming effect of sea ice loss and associated upward turbulent heat fluxes are relatively minor in this event. This result suggests the importance of the synoptically driven warm and moist air intrusion into the Arctic as a primary contributing factor of this extreme Arctic warming event.").

[157] Notz D. & Stroeve J. (2016) *Observed Arctic sea-ice loss directly follows anthropogenic CO_2 emission*, SCIENCE 354(6313):747–750, 747 ("Arctic sea ice is retreating rapidly, raising prospects of a future ice-free Arctic Ocean during summer. Since climate-model simulations of the sea-ice loss differ substantially, we here use a robust linear relationship between monthly-mean September sea-ice area and cumulative CO_2 emissions to infer the future evolution of Arctic summer sea ice directly from the observational record. The observed linear relationship implies a sustained loss of 3 ± 0.3 m^2 of September sea-ice area per metric ton of CO_2 emission."); *see also* Stroeve J. & Notz D. (2018) *Changing state of Arctic sea ice across all seasons*, ENVTL. RESEARCH LETTERS 13(103001):1–23, 12 ("For example, Niederdrenk and Notz (2018) derive from observational records that in the long term, 3.3–4 million km^2 of September Arctic sea ice are lost per °C of annual mean global warming, while the sensitivity in March is around 1.6 million km^2 of sea ice loss per °C of annual mean global warming.").

[158] Notz D. & Stroeve J. (2016) *Observed Arctic sea-ice loss directly follows anthropogenic CO_2 emission*, SCIENCE 354(6313):747–750, 747 ("Arctic sea ice is retreating rapidly, raising prospects of a future ice-free Arctic Ocean during summer. Since climate-model simulations of the sea-ice loss differ substantially, we here use a robust linear relationship between monthly-mean September sea-ice area and cumulative CO_2 emissions to infer the future evolution of Arctic summer sea ice directly from the observational record. The observed linear relationship implies a sustained loss of 3 ± 0.3 m^2 of September sea-ice area per metric ton of CO_2 emission. Based on this sensitivity, Arctic sea-ice will be lost throughout September for an additional 1000 Gt of CO_2 emissions. Most models show a lower sensitivity, which is possibly linked to an underestimation of the modeled increase in incoming longwave radiation and of the modeled Transient Climate Response.").

[159] Notz D. & Stroeve J. (2016) *Observed Arctic sea-ice loss directly follows anthropogenic CO_2 emission*, SCIENCE 354(6313):747–750, 748 ("[T]he observed linear relationship allows us to estimate a sensitivity of 3.0 ± 0.1 m^2 of September Arctic sea-ice loss per ton of anthropogenic CO_2 emissions during the observational period 1953–2015. This number is sufficiently intuitive to allow one to grasp the contribution of personal CO_2 emissions to the loss of Arctic sea ice. For example, based on the observed sensitivity, the average personal CO_2 emissions of several metric tons per year can be directly linked to the loss of tens of m^2 of Arctic sea ice every single year."); *see also* Stroeve J. & Notz D. (2018) *Changing state of Arctic sea ice across all seasons*, ENVTL. RESEARCH LETTERS 13(103001):1–23, 19 ("Extrapolating the linear relationships into the future, we find that the Arctic Ocean completely loses its ice cover throughout August and September for an additional roughly 800 ± 300 Gt of anthropogenic CO_2 emissions. For an additional 1400 ± 300 Gt of anthropogenic CO_2 emissions, we estimate the Arctic to become sea-ice free from July throughout October (see Notz and Stroeve 2018 for details on these estimates, in particular regarding the uncertainty arising from internal variability). Given today's emission rate of about 40 Gt CO_2 per year, the time window is closing very rapidly to preserve Arctic sea-ice cover all year round.").

[160] Gagné M.-E., *et al.* (2017) *Aerosol-driven increase in Arctic sea ice over the middle of the twentieth century*, GEOPHYSICAL RESEARCH LETTERS 44:7338–7346, 7345 ("Indeed, the ice-expanding influence of aerosol forcing was able to offset the greenhouse-gases-forced decline in ice cover for the period 1950–1975. Further, these results

implý that caution is needed in inferring the future rate of sea ice decline with respect to cumulative CO_2 emissions from that observed over the past 60 years [*Notz and Stroeve*, 2016], since aerosol emissions increased over the historical period but are projected to decrease in the future [*Gagné et al.*, 2015].").

[161] Gagné M.-E., *et al.* (2017) *Aerosol-driven increase in Arctic sea ice over the middle of the twentieth century*, GEOPHYSICAL RESEARCH LETTERS 44:7338–7346, 7344 ("The simulations indicate that the positive trend in sea ice extent over the 1950–1975 period was mainly due to anthropogenic aerosols, and with a smaller positive contribution from natural variability, partially offset by a negative trend due to increasing greenhouse gases (compare the AER and GHG bars in Figure 5a). Indeed, the magnitude of the total radiative forcing from aerosols increased significantly over the midtwentieth century due to a strong increase in sulphate aerosols [*Skeie et al.*, 2010; *Myhre et al.*, 2014] (see supporting information Figure S6), which scatters solar radiation and thus results in a net cooling of the climate system [*Shindell and Faluvegi*, 2009; *Skeie et al.*, 2010; *Myhre et al.*, 2014; *Sand et al.*, 2013]. For the period from 1975 to 2005, the negative trend in Arctic sea ice extent was primarily associated with greenhouse gas forcing although a significant but weak contribution can be seen in the aerosol-only simulations. After 1975, the forcing from continuously increasing GHG concentrations and black carbon emissions [*Skeie et al.*, 2010; *Myhre et al.*, 2014] (see supporting information Figure S6), an absorbing aerosol that causes an overall warming effect in the Arctic [*Shindell and Faluvegi*, 2009; *Skeie et al.*, 2010; *Sand et al.*, 2013; *Myhre et al.*, 2014], and the forcing from declining sulphate aerosol loading [*Skeie et al.*, 2010; *Myhre et al.*, 2014; *Yang et al.*, 2014] (see supporting information Figure S6) led to a net warming of the Arctic [*Polyakov et al.*, 2003a; *Johannessen et al.*, 2004; *Gillett et al.*, 2008; *Semenov and Latif* , 2012; *Shindell and Faluvegi*, 2009; *Fyfe et al.*, 2013; *Sand et al.*, 2013; *Yang et al.*, 2014].").

[162] Zhang J., *et al.* (2012) *Recent changes in the dynamic properties of declining Arctic sea ice: A model study*, GEOPHYSICAL RESEARCH LETTERS 39(L20503):1–6, 5 ("As the ice cover becomes thinner and weaker, ice motion may approach a state of free drift not only in summer but also in parts of spring and fall. Thus the ice cover will be more sensitive to changes in wind forcing. While there is little trend in wind forcing on interannual and decadal time scales during 1979–2011, the ice cover may be more susceptible to shorter-term atmospheric changes such as storms or strong southerly wind anomalies that contributed to the drastic ice retreat in 2007 [Overland et al., 2008; Zhang et al., 2008]. This may pose more challenges in forecasts of Arctic sea ice, particularly ice edge locations, on weekly to seasonal time scales.").

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

[164] Day J. J. & Hodges K. I. (2018) *Growing Land-Sea Temperature Contrast and the Intensification of Arctic Cyclones*, GEOPHYSICAL RESEARCH LETTERS 45:3673–3681, 3680 ("Further, because climate change is increasing land-sea contrasts in the Arctic, it seems highly likely that the circulation patterns typical of years with strong AFZ will become more common as the climate warms. Indeed, strengthening of the mean temperature gradients in the AFZ is a robust feature of future climate projections as is an increase in the strength of the Arctic Front Jet (Mann et al., 2017; Nishii et al., 2014). This study shows that this linkage between surface temperature gradients and atmospheric circulation is important for Arctic cyclones, adding weight to previous studies.").

[165] Zhang J., *et al.* (2013) *The impact of an intense summer cyclone on 2012 Arctic sea ice retreat*, GEOPHYSICAL RESEARCH LETTERS 40:720–726, 722 ("The rapid reduction in ice volume during the storm is due to enhanced ice melt (Figures 3a–3d). The simulated total ice melt is 0.12×10^3 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). It is no surprise that, because of the elevated ice melt, satellite observations showed a much-reduced ice extent there by 10 August (e.g., Figures 1h and 4a).").

[166] Zhang J., *et al.* (2013) *The impact of an intense summer cyclone on 2012 Arctic sea ice retreat*, GEOPHYSICAL RESEARCH LETTERS 40:720–726, 725 ("Stronger winds during the cyclone not only increase ice motion and hence deformation, but also generate waves and wave-induced ice fragmentation.").

[167] Zhang J., *et al.* (2013) *The impact of an intense summer cyclone on 2012 Arctic sea ice retreat*, GEOPHYSICAL RESEARCH LETTERS 40:720–726, 725 ("Model results indicate that the early August 2012 cyclone did affect the September minimum Arctic sea ice extent but only by a relatively small amount. Nonetheless, the simulated impact of the cyclone on sea ice is strong during and in the immediate aftermath of the cyclone. When the cyclone reached the ICAPS during 6–8 August, ice melt was enhanced and ice thickness decreased rapidly in much of the Canada Basin. The enhanced ice melt is attributed mainly to an increase in bottom melt due to stronger upward ocean heat transport. The increase in upward heat transport is caused by enhanced heat entrainment from the NSTM layer to the SML, driven by strong winds and ice motion, such that the heat content in the NSTM layer is reduced during the storm.").

[168] Zhang J., *et al.* (2013) *The impact of an intense summer cyclone on 2012 Arctic sea ice retreat*, GEOPHYSICAL RESEARCH LETTERS 40:720–726, 725 ("Although the cyclone lasted only a few days, the strong impact of enhanced bottom melt on ice extent persists for more than a half month. Ice extent was reduced by as much as 0.48×10^6 km^2 in the aftermath of the cyclone. Beyond a half month, the effect of the cyclone subsides.").

[169] Zhang J., *et al.* (2013) *The impact of an intense summer cyclone on 2012 Arctic sea ice retreat*, GEOPHYSICAL RESEARCH LETTERS 40:720–726, 725 ("There are some key differences between the conditions leading to the new record set in 2012 and those leading to the previous record set in 2007. In summer 2012, the simulated ice cover is much thinner (Figure 2b) and thus more vulnerable to changes in atmospheric and oceanic forcing and easier to shrink. The cyclone was intense enough to cause stronger upward heat transport in a normally well-stratified summer ocean, leading to enhanced bottom ice melt. Because of the short duration of the storm, ice mass advection is not a significant factor; cyclone-enhanced ice motion only advances ice by additional 9 km d^{-1} on average. In the summer of 2007, sustained southerly wind anomalies drove ice away from much of the Pacific sector toward Fram Strait during much of the melting season from July to September, leaving behind a large area of open water and thin ice where ice-albedo feedback caused amplified ice melt [Zhang et al., 2008; Lindsay et al., 2009].").

[170] Francis J. A. & Vavrus S. J. (2012) *Evidence linking Arctic amplification to extreme weather in mid-latitudes*, GEOPHYSICAL RESEARCH LETTERS 39(L06801):1–6, 2 ("The differential warming of the Arctic relative to mid-latitudes is the key linking AA with patterns favoring persistent weather conditions in mid-latitudes. Two separate effects on upper-level characteristics are anticipated: weaker poleward thickness gradients cause slower zonal winds, and enhanced high-latitude warming causes 500 hPa heights to rise more than in mid-latitudes, which elongates the peaks of ridges northward and increases wave amplitude. Both of these effects should slow eastward wave progression."); *see also* Francis J. A. & Vavrus S. J. (2015) *Evidence for a wavier jet stream in response to rapid Arctic warming*, ENVTL. RESEARCH LETTERS 10(014005):1–12, 1 ("New metrics and evidence are presented that support a linkage between rapid Arctic warming, relative to Northern hemisphere mid-latitudes, and more frequent high-amplitude (wavy) jet-stream configurations that favor persistent weather patterns. We find robust relationships among seasonal and regional patterns of weaker poleward thickness gradients, weaker zonal upper-level winds, and a more meridional flow direction. These results suggest that as the Arctic continues to warm faster than elsewhere in response to rising greenhouse-gas concentrations, the frequency of extreme weather events caused by persistent jet-stream patterns will increase."); *and* Screen J. A. & Simmonds I. (2013) *Exploring links between Arctic amplification and mid-latitude weather*, GEOPHYSICAL RESEARCH LETTERS 40:959–964, 960 ("In the first framework, we define the waves in terms of the latitude of selected Z500 isopleths. In this framework, wave amplitude describes the meridional extent of the meanders in the flow, hereafter referred to as "meridional amplitude." The isopleths used were 5400, 5500, 5700, and 5600 m for winter (January–February–March; JFM), spring (April–May–June; AMJ), summer (July–August–September; JAS), and autumn (October–November–December; OND), respectively. These selected isopleths and seasonal definitions are consistent with FV12. We calculated the latitude of the selected Z_{500} isopleth (denoted θ_{iso}) at each longitude. Because the selected isopleth commonly lies between grid points, θ_{iso} was approximated by linear interpolation from the neighboring grid points. For longitudes where there were multiple instances of the selected isopleth, the most southerly intersection was chosen. In the second framework, we define the waves in terms of the Z_{500} around the 45 N latitude circle. In this framework, wave amplitude describes the height and depth of ridges and troughs around 45 N, hereafter referred to as "zonal amplitude." In what follows we are careful to use the colloquial terms "ridge" and "trough" only in the context of zonal waves and "meander" only in the context of meridional waves. The two measures of amplitude reflect different characteristics of the mid-latitude circulation and changes therein, and have differing implications for mid-latitude weather, which will be discussed later.").

[171] Francis J. A. & Vavrus S. J. (2012) *Evidence linking Arctic amplification to extreme weather in mid-latitudes*, GEOPHYSICAL RESEARCH LETTERS 39(L06801):1–6, 1 ("Arctic amplification (AA) – the observed enhanced warming in high northern latitudes relative to the northern hemisphere – is evident in lower-tropospheric temperatures and in 1000-to-500 hPa thicknesses. Daily fields of 500 hPa heights from the National Centers for Environmental Prediction Reanalysis are analyzed over N. America and the N. Atlantic to assess changes in north-south (Rossby) wave characteristics associated with AA and the relaxation of poleward thickness gradients. Two effects are identified that each contribute to a slower eastward progression of Rossby waves in the upper-level flow: 1) weakened zonal winds, and 2) increased wave amplitude. These effects are particularly evident in autumn and winter consistent with sea-ice loss, but are also apparent in summer, possibly related to earlier snow melt on high-latitude land. Slower progression of upper-level waves would cause associated weather patterns in mid-latitudes to be more persistent, which may lead to an increased probability of extreme weather events that result from prolonged conditions, such as drought, flooding, cold spells, and heat waves."); *see also* Francis J. A. & Vavrus S. J. (2015) *Evidence for a wavier jet stream in response to rapid Arctic warming*, ENVTL. RESEARCH LETTERS 10(014005):1–12, 9 ("Here we provide evidence demonstrating that in areas and seasons in which poleward gradients have weakened in response to AA, the upper-level flow has become more meridional, or wavier. Moreover, the frequency of days with high-amplitude jet-stream configurations has increased during recent years. These high-amplitude patterns are known to produce persistent weather patterns that can lead to extreme weather events. Notable examples of these types of events include cold, snowy winters in Eastern North America during winters of 2009/10, 2010/11, and 2013/14; record-breaking snowfalls in Japan and SE Alaska during winter 2011/12; and Middle-East floods in winter 2012/2013, to name only a few."); *and* Ahlstrøm A. P., *et al.* (2017) *Abrupt shift in the observed runoff from the southwestern Greenland ice sheet*, SCIENCE ADVANCES 3(e1701169):1–7, 4 ("Increased frequency in blocking events and meridional flow has been linked to a wavier jet stream because of a reduced poleward temperature gradient, in turn an effect of the Arctic amplification of global warming (39). Here, we present observational evidence of an abrupt change in the runoff regime in southwest Greenland occurring in 2003, with an 80% increase in ice sheet runoff between the 1976– 2002 and 2003–2014 periods, and link this to an increase in persistent summertime anticyclonic flow over Greenland through correlation with the GBI and a southward shift in the origin of the air masses arriving in the Tasersiaq catchment in southwest Greenland. We consider it likely that this change in the runoff regime driven by atmospheric changes could be further reinforced by the growth of ice layers in the firn of the lower accumulation area of the ice sheet, reducing meltwater retention (20).").

[172] Francis J. A. & Vavrus S. J. (2015) *Evidence for a wavier jet stream in response to rapid Arctic warming*, ENVTL. RESEARCH LETTERS 10(014005):1–12, 8 ("Overall, the pattern of frequency change is consistent with expectations of a more amplified jet stream in response to rapid Arctic warming. Amplified jet-stream patterns are associated with a variety of extreme weather events (i.e., persistent heat, cold, wet, and dry), thus an increase in amplified patterns suggests that these types of extreme events will become more frequent in the future as AA continues to intensify in all seasons. These results may also provide a mechanism to explain observed associations between sea-ice loss and continental heat waves, cold spells, heavy snowfall, and anomalous summer precipitation patterns in Europe."); *see also*

[173] Screen J. A. & Simmonds I. (2013) *Exploring links between Arctic amplification and mid-latitude weather*, GEOPHYSICAL RESEARCH LETTERS 40:959–964, 963 ("Figure 4c shows the meanders defined by a selected isopleth in Figure 4a and the same isopleth in Figure 4b. In response to AA the meanders shift poleward, but not equally at all longitudes. This reflects that the northward meanders are located in a region of larger Z500 increase than the southward meanders, and hence the former shift poleward more than the latter. Thus, meridional amplitude increases in the presence of AA. Figure 4d shows the waves defined by sampling Z500 along a line of latitude (dashed lines in Figures 4a and 4b). In this case, the wave shifts equally at all longitudes and zonal amplitude remains unchanged. Furthermore, it is possible for zonal amplitude to decrease at all latitudes and for meridional amplitude to still increase, if the influence of AA is greater than the influence of decreased zonal amplitude. We propose that this scenario explains the opposing trends in meridional and zonal amplitude in some seasons and sectors."). *See also* Figure 4 from Screen and Simmonds 2013; *and* Hanna E., *et al.* (2016) *Greenland Blocking Index 1851–2015: a regional climate change signal*, INT'L. J. CLIMATOLOGY 36:4847–4861, 4860 ("The combination of these possible forcing effects through Arctic Amplification, which is traditionally thought to be greatest in winter due to a lagged response to summer sea-ice losses (Deser *et al.*, 2010; Screen and Simmonds, 2010) and limited ice-/snow-melt during the cold season, may have recently led to more frequent destabilization of the winter jet and polar vortex. However, as this does not happen every year, this may have the effect of making the winter atmospheric circulation in mid-high northern latitudes more variable on an interannual basis. This perhaps reflects interplay between the tropical, Arctic and mid-latitude influences outlined above, together with internal atmospheric variability. Future

modelling and dynamical process studies should focus on defining the relative influences of the various climatic forcings and feedbacks discussed above on Greenland Blocking changes. However, whatever the causes of these recent changes, our GBI index effectively captures them and enables them to be placed in a longer-term climatic context.").

[174] Cohen J., *et al.* (2018) *Warm Arctic episodes linked with increased frequency of extreme winter weather in the United States*, NATURE COMMUNICATIONS 9(869):1–12, 2 ("Anthropogenic global warming is widely expected to increase certain types of weather extremes, including more intense and frequent heat waves and droughts as well as heavy precipitation events. Surprisingly, however, over the past two to three decades, the increase in extreme weather has included more (not fewer) severe cold-air outbreaks and heavy snowfalls observed both in North America and Eurasia.").

[175] Cohen J., *et al.* (2018) *Warm Arctic episodes linked with increased frequency of extreme winter weather in the United States*, NATURE COMMUNICATIONS 9(869):1–12, 2–3 ("A strong relationship between a warmer Arctic and increased frequency of severe winter weather is apparent for all stations east of the Rockies, with the strongest association in the eastern third of the US, where we find a statistically significant ($p < 0.01$) and nearly linear relationship between Arctic height changes throughout the troposphere and AWSSI. When Arctic heights are at their lowest (PCH $< \sim -1$), severe winter weather is unlikely."); Cohen J., *et al.* (2018) *Warm Arctic episodes linked with increased frequency of extreme winter weather in the United States*, NATURE COMMUNICATIONS 9(869):1–12, 6 ("Modeling studies have reported divergent conclusions as to whether AA contributes to less or more snowfall. We computed the return period of varying thresholds of snowfall across the US before (1950–1989) and after (1990–2016) the emergence of AA (Fig. 9). Consistent with our earlier results that a warmer Arctic favors heavier snowfalls, we find that across the northeastern US, heavy snowfalls are generally more frequent since 1990, and in many cities the most extreme snowfalls have occurred primarily during recent decades. In contrast, severe snowfalls in the western US have in general decreased during the AA period. For most cities shown in Fig. 9, the snowfall return periods were found to differ between the two periods with a confidence level greater than 95%.").

[176] Cohen J., *et al.* (2018) *Warm Arctic episodes linked with increased frequency of extreme winter weather in the United States*, NATURE COMMUNICATIONS 9(869):1–12, 5 ("To compare Arctic versus tropical influences on severe winter weather events, the analysis was repeated but with the PCH index replaced with the El Niño/Southern Oscillation (ENSO) index, as the tropics are generally thought to be the most important remote driver of mid-latitude weather. In Supplementary Figure 1 we plot the composite AWSSI relative to the standardized Niño 3.4. For all stations across the country, there is no preferential value of AWSSI with ENSO variability, though there does seem to be a decline in severe winter weather for the most extreme El Niño values. This finding suggests that Arctic variability has a stronger influence on severe winter weather events than does ENSO variability.").

[177] Cvijanovic I., *et al.* (2017) *Future loss of Arctic sea-ice cover could drive a substantial decrease in California's rainfall*, NATURE COMMUNICATIONS 8(1947):1–10, 1 ("From 2012 to 2016, California experienced one of the worst droughts since the start of observational records. As in previous dry periods, precipitation-inducing winter storms were steered away from California by a persistent atmospheric ridging system in the North Pacific. Here we identify a new link between Arctic sea-ice loss and the North Pacific geopotential ridge development. In a two-step teleconnection, sea-ice changes lead to reorganization of tropical convection that in turn triggers an anticyclonic response over the North Pacific, resulting in significant drying over California. These findings suggest that the ability of climate models to accurately estimate future precipitation changes over California is also linked to the fidelity with which future sea-ice changes are simulated. We conclude that sea-ice loss of the magnitude expected in the next decades could substantially impact California's precipitation, thus highlighting another mechanism by which human-caused climate change could exacerbate future California droughts.").

[178] Cvijanovic I., *et al.* (2017) *Future loss of Arctic sea-ice cover could drive a substantial decrease in California's rainfall*, NATURE COMMUNICATIONS 8(1947):1–10, 8 ("As a final remark, we note that the pronounced Arctic sea-ice loss over the satellite era is likely human-induced, arising from anthropogenic warming caused by greenhouse gas increases. Our study thus identifies yet another pathway by which human activities could affect the occurrence of future droughts over California—through human-induced Arctic sea-ice decline.").

[179] Cvijanovic I., *et al.* (2017) *Future loss of Arctic sea-ice cover could drive a substantial decrease in California's rainfall*, NATURE COMMUNICATIONS 8(1947):1–10, 6 ("As seen from Supplementary Fig. 8a, low Arctic sea-ice increases the likelihood of drier California, but does not result in drier conditions over California every single year. On average, when considering the 20-year mean, there is a 10–15% decrease in California's rainfall (Fig. 2c). Comparison with the driest 3-year interval within this 20-year period (Supplementary Fig. 8b) indicates that the magnitude of the simulated precipitation response is comparable to the magnitude of changes in ERA-Interim during the most recent drought.").

[180] Cvijanovic I., *et al.* (2017) *Future loss of Arctic sea-ice cover could drive a substantial decrease in California's rainfall*, NATURE COMMUNICATIONS 8(1947):1–10, 6 ("This consistency does not, however, constitute compelling evidence that the 2012–2016 California drought is attributable to Arctic sea-ice changes. Rather, it illustrates that some of the atmospheric features of the droughts driven by Arctic sea-ice loss may resemble those of the most recent California drought.").

[181] Cvijanovic I., *et al.* (2017) *Future loss of Arctic sea-ice cover could drive a substantial decrease in California's rainfall*, NATURE COMMUNICATIONS 8(1947):1–10, 8 ("We emphasize, however, that sea-ice loss is one of multiple factors implicated in driving the described atmospheric circulation and precipitation changes. In simulations of historical and future climate, multiple hemispherically asymmetric forcings are changing simultaneously. Some of these forcings affect sea-ice cover, thus hampering the elucidation of links between Arctic sea-ice loss and California's rainfall. This is one advantage of the experimental configuration used here. By design, the convection, atmospheric circulation, and precipitation responses described here are directly related to sea-ice changes in each hemisphere, and not to changes in anthropogenic and natural forcings, or deep-ocean feedbacks.").

[182] Jahn A. (2018) *Reduced probability of ice-free summers for 1.5 °C compared to 2 °C warming*, NATURE CLIMATE CHANGE 8:409–413, 412 ("Hence, if temperatures should eventually decline again, sea ice will increase at the same rate per °C as it was lost. This potential for a recovery of sea ice when temperatures decline is shown in the the 1.5 °C OS simulation, and agrees with previous work on the reversibility of Arctic sea-ice loss. However, to return sea ice to present-day conditions, the atmospheric CO_2 concentrations need to be reduced below current values.").

[183] Hezel P. J., *et al.* (2014) *Modeled Arctic sea ice evolution through 2300 in CMIP5 extended RCPs*, CRYSOPHERE 8:1195–1204, 1197 ("Model studies have consistently shown that the Arctic sea ice recovers in experiments after the model is forced into an ice-free state. This is true for both annually ice-free conditions achieved via radiative forcing (Armour et al., 2011; Ridley et al., 2012) and for seasonally ice-free conditions achieved by imposed removal (Tietsche et al., 2011). Such results have been obtained in studies using a single model, and the CMIP5 archive under RCP2.6 affords a demonstration of reversibility of seasonal sea ice decline across multiple models, albeit for a relatively small change in forcing. In experiments using a change of forcing similar to RCP2.6 under the ENSEMBLES project (Johns et al., 2011), the sea ice did not show recovery on timescales up through 2100 (Körper et al., 2013). In Sect. 5, we examine the reversibility shown under RCP2.6 and demonstrate that the extended simulation through 2300 is required to distinguish the forced response from the variability.").

[184] Hezel P. J., *et al.* (2014) *Modeled Arctic sea ice evolution through 2300 in CMIP5 extended RCPs*, CRYSOPHERE 8:1195–1204, 1203 ("From a policy perspective, extended RCP2.6 indicates that a recovery of Arctic sea ice could begin if and when policies to reduce global greenhouse gas concentrations and hence radiative forcing are implemented. Extended RCP4.5 further shows that a plateau in the forcing may not be sufficient to prevent continued Arctic sea ice loss and a seasonally ice-free state even if the decrease in forcing begins before the disappearance of summer sea ice. In practice, a reduction in forcing to prevent further sea ice loss needs to be sufficiently large to dominate the recalcitrant warming expected from heat storage in slowly evolving parts of the climate system (e.g., deep ocean) (Held et al., 2010). The threshold at which a forcing reduction maintains a constant global mean temperature would itself be a function of the estimated equilibrium and transient climate sensitivities of the Earth system. As the RCP scenarios do not incorporate interactive carbon cycle processes and feedbacks, the impact of such processes would need to be considered in the design of any strategies to reduce radiative forcing.").

[185] Desch S. J., *et al.* (2017) *Arctic ice management*, EARTH'S FUTURE 5:107–127, 107 ("As the Earth's climate has changed, Arctic sea ice extent has decreased drastically. It is likely that the late-summer Arctic will be ice-free as soon as the 2030s. This loss of sea ice represents one of the most severe positive feedbacks in the climate system, as sunlight that would otherwise be reflected by sea ice is absorbed by open ocean. It is unlikely that CO_2 levels and mean temperatures can be decreased in time to prevent this loss, so restoring sea ice artificially is an imperative. 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.").

[186] Desch S. J., *et al.* (2017) *Arctic ice management*, EARTH'S FUTURE 5:107–127, 121 ("We have presented a concept of a buoy-mounted windpump system that could carry out the required pumping specified above. We have

estimated the cost to construct and deploy each device to be comparable to $50,000. To deploy one device per 0.1 km^2 over the entire Arctic Ocean would cost on the order of $5 trillion, but if devices are deployed over only 10% of the Arctic Ocean, over 10 years, the costs are only $50 billion per year. The largest obstacles include producing the required steel and delivering the devices to the Arctic. Deployment over only 10% of the Arctic, though, would require consumption of only about 13% of the U.S. steel production, and roughly 5% of worldwide container ship capacity. These are expensive propositions, but within the means of governments to carry out on a scale comparable to the Manhattan Project.").

[187] Field L., *et al.* (2018) *Increasing Arctic Sea Ice Albedo Using Localized Reversible Geoengineering*, EARTH'S FUTURE 6:882–901, 900 ("The materials used in the Ice911 treatment are considered nontoxic, consisting of sand component silica, and in testing to date, they have shown no adverse impact on wildlife. The risks of an ice-free Arctic include the Arctic's contribution to increased world-wide temperatures through absorption rather than reflection of incoming summer-time solar radiation."); *see also* Ice911, "It's Time to Restore Arctic Ice" (*last accessed* 31 August 2018).

[188] Desch S. J., *et al.* (2017) *Arctic ice management*, EARTH'S FUTURE 5:107–127, 122 ("We stress that even if the technical problems associated with AIM were solved, and the ice in the Arctic were to thicken as we (tentatively) predict, this would not "solve" all the problems of anthropogenic climate change. Many severe problems would persist, notably the acidification of the ocean; ocean pH is decreasing by 0.0019 units per year due to increased CO_2 in the atmosphere [*Doney et al*., 2009]. We consider AIM to be a potential means of arresting or possibly reversing the loss of ice in the Arctic, thereby interrupting the ice-albedo feedback. We predict some reduction in direct radiative forcing that may serve to cool the Earth, but the primary advantage of AIM is to prevent the loss of sea ice and the increase in sunlight absorption that would accompany it. Other problems like ocean acidification would have to be solved by other means (e.g., reduction in CO_2 emission and/or carbon dioxide capture and sequestration). AIM is just one potential component in a multipronged strategy for dealing with all the problems of climate change.").

[189] Desch S. J., *et al.* (2017) *Arctic ice management*, EARTH'S FUTURE 5:107–127, 121–122 ("There are questions about the feasibility: does the proposed technique actually lead to local thickening of the ice over a year? Would the proposed device actually work robustly over multiple seasons, or are conditions in the Arctic too harsh? Could a system be designed to passively deliver water over a 0.1 km^2 area, or is some means of active control necessary? Can the common problems machinery faces in Arctic conditions be solved? Also, because this technique generates ice by putting seawater at the surface, the ice would contain more salt than if the seawater froze to the bottom of the sea ice. The difference is probably slight, as first-year sea ice is naturally salty, becoming fresher each year by the process of brine rejection. But it is not clear how this would affect summer melting or the strength of the ice. Questions about the feasibility of the device and its local effects are probably best solved by building a prototype and experimenting with it in the field. …There are also questions about the collateral effects of producing and deploying such a large number (at least 10 million) buoys across the Arctic. We have argued that the impact on CO_2 emissions is probably negligible, but the environmental impact of the manufacture of so many devices, comparable in scope to the automotive industry, should be assessed. The effects of the presence of the devices themselves on local Arctic ecosystems, and their interaction with sea life, should be assessed as well.").

[190] Jackson L. S., *et al.* (2015) *Assessing the controllability of Arctic sea ice extent by sulfate aerosol geoengineering*, GEOPHYSICAL RESEARCH LETTERS 42:1223–1231, 1223 ("In an assessment of how Arctic sea ice cover could be remediated in a warming world, we simulated the injection of SO_2 into the Arctic stratosphere making annual adjustments to injection rates. We treated one climate model realization as a surrogate "real world" with imperfect "observations" and no rerunning or reference to control simulations. SO_2 injection rates were proposed using a novel model predictive control regime which incorporated a second simpler climate model to forecast "optimal" decision pathways. Commencing the simulation in 2018, Arctic sea ice cover was remediated by 2043 and maintained until solar geoengineering was terminated. We found quantifying climate side effects problematic because internal climate variability hampered detection of regional climate changes beyond the Arctic. Nevertheless, through decision maker learning and the accumulation of at least 10 years time series data exploited through an annual review cycle, uncertainties in observations and forcings were successfully managed.").

[191] Jackson L. S., *et al.* (2015) *Assessing the controllability of Arctic sea ice extent by sulfate aerosol geoengineering*, GEOPHYSICAL RESEARCH LETTERS 42:1223–1231, 1230 ("Our injection amounts (up to 12 $Tg[SO_2]/yr$) were large, equivalent to more than 50% of the SO_2 emissions from the 1991 Mount Pinatubo eruption [Guo et al., 2004], and would require more than 1000 KC-135 tanker aircraft flights per day during peak injection periods [Robock et al., 2009]. It remains uncertain whether the stratospheric aerosol concentration would increase linearly with injection rate [Heckendorn et al., 2009] and whether an efficient distribution of aerosol particle size could be sustained [Niemeier et al., 2011]. Accelerated climate change on termination of SRM, also demonstrated

by Jones et al. [2013], shows climate to be vulnerable to unplanned disruption of SRM injections [Baum et al., 2013]. We found statistically significant differences in regional climate persisted into the 2090s even when global mean climate had returned close to the nongeoengineered state.").

[192] World Meteorological Organization (WMO) (2018) SCIENTIFIC ASSESSMENT OF OZONE DEPLETION: 2018, Global Ozone Research and Monitoring Project–Report No. 58, 6.16 ("Column ozone changes as the result of stratospheric aerosol geoengineering therefore depends on the injection amount, timing (ODS loading), and injection strategy (influencing aerosol size and location; Appendix 6A). Relatively small and constant injections of 2.5–4 Tg S yr^{-1} between 2020 and 2070, which would result in 0.5°C of surface cooling, are calculated to lead to an approximately 4% reduction in the global stratospheric column ozone for 2020 and only 1% reduction by 2070 (Pitatry et al., 2014; Xia et al., 2017). Much larger injection amounts that would lead to a surface temperature cooling of around 2°C in 2040– 2050, based on a single model study, would result in reductions in column ozone of 28–40% in October over Southern Hemisphere (SH) high latitudes and 8–18% for NH high latitudes in March, with varying values depending on the injection altitude (Tilmes et al., 2018). Injections closer to the tropopause cause a stronger dynamical response and could result in up to an 8% increase in column ozone in NH winter mid- and high latitudes. A single modeling transient simulation based on RCP8.5 greenhouse gas forcings with continuously increasing SO_2 injections between 2020 and 2099 and decreasing ODSs would result in approximately constant change in column ozone in high polar latitudes (20–23% in October over the SH and 10–12% in March over the NH polar latitudes) and slightly larger (3–5%) column ozone values compared to non-geoengineering conditions for tropics and winter northern mid-latitudes by the end of the 21st century (Richter et al., 2018).").

[193] Schaefer K., *et al.* (2011) *Amount and timing of permafrost carbon release in response to climate warming*, TELLUS SERIES B CHEMICAL & PHYSICAL METEOROLOGY 63(2):165–180, 165 ("Permafrost is soil at or below 0ºC for at least two consecutive years."); *see also* Arctic Monitoring and Assessment Programme (AMAP) (2017) ADAPTATION ACTIONS FOR A CHANGING ARCTIC: PERSPECTIVES FROM THE BARENTS AREA, 12 ("Permafrost (cryotic soils) is defined as soil(s) that remains at or below the freezing point of water for at least two consecutive years. Permafrost can only develop when the mean annual air temperature is low enough and snowfall in winter is limited, to allow heat flux from the ground.").

[194] Chadburn S. E., *et al.* (2017) *An observation-based constraint on permafrost loss as a function of global warming*, NATURE CLIMATE CHANGE 7:340–344, 340 ("The estimated permafrost area is 15.5 million km^2 using this technique (12.0–18.2 million km^2 using minimum/maximum curves), which compares well to 15.0 million km^2 from observations (12.6–18.4 million km^2).").

[195] Schaefer K., *et al.* (2014) *The Impact of the Permafrost Carbon Feedback on Global Climate*, Environmental Research Letters 9:1–9, 2 ("If temperatures rise and permafrost thaws, the organic material will also thaw and begin to decay, releasing carbon dioxide (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., *et al.* (2011) *Amount and timing of permafrost carbon release in response to climate warming*, TELLUS SERIES B CHEMICAL & PHYSICAL METEOROLOGY 63(2):165–180, 166 ("The permafrost carbon feedback (PCF) is an amplification of surface warming due to the release into the atmosphere of carbon currently frozen in permafrost (Fig. 1). As atmospheric 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).").

[196] Abbott B. W., *et al.* (2016) *Biomass Offsets Little to None of Permafrost Carbon Release from Soils, Streams, and Wildfire: an Expert Assessment*, ENVTL. RESEARCH LETTERS 11(034014):1–13, 9. ("Over the past several decades, the permafrost region has removed an average of 500 Tg carbon yr^{-1} from the atmosphere (McGuire et al 2009, Pan et al 2011, Hayes et al 2011). Combining our estimates of biomass uptake with a recent projection of permafrost soil carbon release (Schuur et al 2013) suggests that the permafrost region will become a carbon source to the atmosphere by 2100 for all warming scenarios…[B]ecause estimates of change in biomass are similar across warming scenarios but permafrost carbon release is strongly temperature-sensitive, the emissions gap widens for warmer scenarios, resulting in five-times more net carbon release under RCP8.5 than RCP2.6. This suggests that 65 to 85% of permafrost carbon release could be avoided if human emissions are actively reduced—i.e. if emissions follow RCP2.6 instead of RCP8.5….").

[197] Schneider von Deimling T., *et al.* (2015) *Observation-based modelling of permafrost carbon fluxes with accounting for deep carbon deposits and thermokarst activity*, BIOGEOSCIENCES 12:3469–3488, 3470 ("By ultimately increasing the atmospheric concentration of the greenhouse gases CO_2 and CH_4, the carbon release from thawing permafrost regions is considered a potentially large positive feedback in the climate–carbon system (Schaefer et al., 2014; Schuur et al., 2015). Given the long millennial timescale processes leading to the build-up of old carbon in permafrost soils, future rapid releases from these deposits are irreversible on a human timescale.").

[198] Schuur E. A. G., *et al.* (2015) *Climate Change and the Permafrost Carbon Feedback*, NATURE 520:171–179, 171 ("Large quantities of organic carbon are stored in frozen soils (permafrost) within Arctic and sub-Arctic regions. A warming climate can induce environmental changes that accelerate the microbial breakdown of organic carbon and the release of the greenhouse gases carbon dioxide and methane. This feedback can accelerate climate change, but the magnitude and timing of greenhouse gas emission from these regions and their impact on climate change remain uncertain."); *see also* Montzka S. A., *et al.* (2011) *Non-CO_2 Greenhouse Gases and Climate Change*, NATURE 476 43–50, 45 ("Taken together, the evidence suggests that the renewed increases in atmospheric CH_4 observed during 2007 and 2008 arose primarily from enhanced natural wetland emissions as a result of anomalously high temperatures in the Arctic and greater than average precipitation in the tropics associated with a persistent La Niña. The causes of the continued increases in 2009 and 2010 are not yet clear, but may be related to the strong La Niña that started in early 2010."); Schädel C., *et al.* (2016) *Potential carbon emissions dominated by carbon dioxide from thawed permafrost soils*, NATURE CLIMATE CHANGE 6:950–953, 950 ("Increasing temperatures in northern high latitudes are causing permafrost to thaw, making large amounts of previously frozen organic matter vulnerable to microbial decomposition. Permafrost thaw also creates a fragmented landscape of drier and wetter soil conditions that determine the amount and form (carbon dioxide (CO_2), or methane (CH_4)) of carbon (C) released to the atmosphere. The rate and form of C release control the magnitude of the permafrost C feedback, so their relative contribution with a warming climate remains unclear."); *and* Hugelius G., *et al.* (2014) *Estimated stocks of circumpolar permafrost carbon with quantified uncertainty ranges and identified data gaps*, BIOGEOSCIENCES 11:6573–6593, 6574 ("As permafrost warming and thaw occurs, large pools of soil organic carbon (SOC) that were previously protected by sub- zero temperatures may become available for mineralization, leading to increased greenhouse gas fluxes to the atmosphere (Schuur et al., 2008).").

[199] Burke E. J., *et al.* (2012) *Uncertainties in the global temperature change caused by carbon release from permafrost thawing*, CRYOSPHERE 6:1063–1076, 1064 ("Schuur et al. (2008) identified four mechanisms that cause permafrost carbon to be released to the atmosphere: (a) active layer thickening, (b) talik formation, (c) thermokarst development, and (d) river and coastal erosion. Climate model projections of permafrost degradation can presently represent (a) and (b) but not (c) or (d).").

[200] 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, 707 ("The simplest form of permafrost thawing to consider from a conceptual and modeling standpoint is active-layer thickening, which leads to thawing of C contained in the uppermost permafrost. Increases in active-layer thickness can occur directly as a result of higher summer air temperatures and the infiltration of precipitation (Nelson et al. 1997, Hinzman et al. 1998), with the latter increasing soil heat content and thermal conductivity.").

[201] 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, 708 ("Eventually, active-layer thickening can be of a magnitude such that the soil does not refreeze completely in the winter, creating a talik, a residual unfrozen soil layer with above-freezing conditions favorable for decomposition. Once formed, a talik can withstand interannual heat deficits that could otherwise lead to refreezing because it generally has high moisture content and heat capacity. Increased active-layer thickness and talik formation, which may be caused by both the indirect and the direct effects of climate warming, act on a widespread basis to thaw permafrost C, both regionally and globally.").

[202] 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, 708 ("Thermokarst terrain develops when ground ice melts and the remaining soil collapses into the space previously occupied by ice volume (figure 5). The degree of thermokarst subsidence is dependent on ground ice distribution and content and thaw magnitude, which in turn are determined locally by soil characteristics, topography, and geomorphology (Shur and Jorgenson 2007). While thermokarst can occur in areas with stable permafrost in response to localized hydrologic changes and near-surface ice melt, thermokarst terrain is widespread in lower latitudes that have been warming since the end of the Little Ice Age (Vitt et al. 2000). In sloped upland areas, thermokarst initiation creates topographic low points that attract water flow toward subsiding areas, feeding back to further thawing through thermal erosion from moving water, and sometimes to active-layer detachment slides—catastrophic erosion of bulk soil material.").

[203] 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, 708 ("In a geographically more limited fraction of the landscape, erosion at river edges and coastal margins can be a significant transfer mechanism of permafrost C (Mars and Houseknecht 2007) (figure 5e, 5f). As with all mechanisms for C loss, river and coastal permafrost erosion that is occurring now is likely to increase with rising sea level, larger storms, and greater river discharge, as has been observed in Russian Arctic rivers (Peterson et al. 2002). Although modest erosion of permafrost occurs each summer, episodic events can be responsible for a significant proportion of river and ocean erosion. These events include the rapid spring breakup of river ice, storm events that produce large waves, and unusual summer precipitation events that increase river flow when permafrost temperatures are at their warmest.").

[204] Burke E. J., *et al.* (2013) *Estimating the Permafrost-Carbon Climate Response in the CMIP5 Climate Models Using a Simplified Approach*, J. CLIMATE 26:4897–4909, 4897 ("To help quantify the permafrost-carbon climate feedback, we need to know how much carbon is vulnerable to release, how fast it will be released, and whether it will be released as carbon dioxide (CO_2) or methane (CH_4). These processes are highly uncertain, spatially variable, and often hard to measure (Schuur and Abbott 2011).").

[205] Burke E. J., *et al.* (2012) *Uncertainties in the global temperature change caused by carbon release from permafrost thawing*, CRYOSPHERE 6:1063–1076, 1071 ("Figure 8 shows how the relative contribution of CH_4 and CO_2 to the total of P-GMT changes over time. During the period 2010 to 2040, the CH_4 emissions drive any (albeit small) increases in P-GMT, with the impact of CH_4 on temperature peaking at more than twice the impact of CO_2. Towards the end of the 21st century, the relatively short CH_4 atmospheric lifetime combined with the larger CO_2 emissions mean that the CO_2 emissions rather than the CH_4 emissions drive the overall temperature increase. However, by 2100, 1/4 of the temperature increase is still caused by CH_4. The ratio of the temperature changes from CH_4 to CO_2 is relatively independent of scenario. On further investigation it was found to be more sensitive to the aerobic decomposition rate used within the carbon decomposition model and also, but less, sensitive to the anaerobic rate.").

[206] Schneider von Deimling T., *et al.* (2015) *Observation-based modelling of permafrost carbon fluxes with accounting for deep carbon deposits and thermokarst activity*, BIOGEOSCIENCES 12:3469–3488, 3480 ("Although permafrost carbon release increases strongly with rising global temperatures (Fig. 3), our results suggest a permafrost-affected global warming of about 0.05 to 0.15 ºC (68% range) until 2100 which is only slightly dependent on the anthropogenic emission pathway. (Fig. 5, Table 2). The quasi path-independency of the permafrost temperature feedback is an expression of the decreasing radiative efficiency under high atmospheric greenhouse gas levels. Long-term warming from the release of newly thawed permafrost carbon can add an additional 0.4 ºC (upper 68% range) to global temperatures until the year 2300. Despite CH_4 release contributing only a few percent to total permafrost carbon release, our analyses suggest that it can cause up to about 40% (upper 68% range) of permafrost-affected warming.").

[207] Knoblauch C., *et al.* (2018) *Methane production as key to the greenhouse gas budget of thawing permafrost*, NATURE CLIMATE CHANGE 8:309–312, 309 ("In drained oxic soils, microorganisms oxidize organic carbon to CO_2.").

[208] Knoblauch C., *et al.* (2018) *Methane production as key to the greenhouse gas budget of thawing permafrost*, NATURE CLIMATE CHANGE 8:309–312, 309 ("Anoxic conditions, which prevail in water-saturated soils, slow down organic carbon decomposition, but enable the formation of both CO_2 and CH_4; the latter has at least a 28-fold GWP of CO_2 (100 years).").

[209] Schädel C., *et al.* (2016) *Potential carbon emissions dominated by carbon dioxide from thawed permafrost soils*, NATURE CLIMATE CHANGE 6:950–953, 952 ("As 3.4 times more soil C is mineralized under aerobic than anaerobic soil conditions, when permafrost thaws and drains, one unit of soil will have a more than three times higher impact on climate change than when the same unit of soil thaws under undrained (anaerobic) conditions. This implies that the permafrost C feedback to climate change could be stronger when a larger percentage of the permafrost zone undergoes thaw in dry and oxygen-rich environments, even under conditions where CO_2 is the dominant gas released to the atmosphere rather than CH_4.").

[210] Knoblauch C., *et al.* (2018) *Methane production as key to the greenhouse gas budget of thawing permafrost*, NATURE CLIMATE CHANGE 8:309–312, 309 ("Permafrost thaw liberates frozen organic carbon, which is decomposed into carbon dioxide (CO_2) and methane (CH_4). The release of these greenhouse gases (GHGs) forms a positive feedback to atmospheric CO_2 and CH_4 concentrations and accelerates climate change. Current studies report a minor importance of CH_4 production in water-saturated (anoxic) permafrost soils and a stronger permafrost carbon–climate feedback from drained (oxic) soils. Here we show through seven-year laboratory incubations that equal amounts of CO_2 and CH_4 are formed in thawing permafrost under anoxic conditions after stable CH_4-

producing microbial communities have established. Less permafrost carbon was mineralized under anoxic conditions but more CO_2–carbon equivalents (CO_2–Ce) were formed than under oxic conditions when the higher global warming potential (GWP) of CH_4 is taken into account. A model of organic carbon decomposition, calibrated with the observed decomposition data, predicts a higher loss of permafrost carbon under oxic conditions (113 ± 58 g CO_2–C kgC^{-1} (kgC, kilograms of carbon)) by 2100, but a twice as high production of CO_2–Ce (241 ± 138 g CO_2–Ce kgC^{-1}) under anoxic conditions. These findings challenge the view of a stronger permafrost carbon-climate feedback from drained soils and emphasize the importance of CH_4 production in thawing permafrost on climate-relevant timescales.").

[211] Knoblauch C., *et al.* (2018) *Methane production as key to the greenhouse gas budget of thawing permafrost*, NATURE CLIMATE CHANGE 8:309–312, 309 ("As permafrost impedes water drainage, water-saturated soils are widespread in permafrost-affected landscapes, although landscape hydrology will probably change in response to permafrost thawing.").

[212] Chadburn S. E., *et al.* (2017) *An observation-based constraint on permafrost loss as a function of global warming*, NATURE CLIMATE CHANGE 7:340–344, 340 ("The estimated permafrost area is 15.5 million km^2 using this technique (12.0–18.2 million km^2 using minimum/maximum curves), which compares well to 15.0 million km^2 from observations (12.6–18.4 million km^2).").

[213] Chadburn S. E., *et al.* (2017) *An observation-based constraint on permafrost loss as a function of global warming*, NATURE CLIMATE CHANGE 7:340–344, 340 ("The observation-based IPA map defines the spatial boundaries of the permafrost zones: continuous, >90% coverage; discontinuous, 50–90% coverage; sporadic, 10–50% coverage; isolated patches, 0–10% coverage."); *see also* Schaefer K., *et al.* (2011) *Amount and timing of permafrost carbon release in response to climate warming*, TELLUS SERIES B CHEMICAL & PHYSICAL METEOROLOGY 63(2):165–180, 171 ("In continuous permafrost regions, permafrost covers 90–100% of the land area, while in discontinuous permafrost regions, permafrost covers 50% to 90% the land area (Brown et al., 1998; Zhang et al., 1999).").

[214] Arctic Monitoring and Assessment Programme (AMAP) (2017) SNOW, WATER, ICE, AND PERMAFROST IN THE ARCTIC: SUMMARY FOR POLICYMAKERS, 5 ("New estimates indicate that Arctic soils hold about 50% of the world's soil carbon. While thawing permafrost is expected to contribute significantly to future greenhouse gas emissions, the amount released over the past 60 years has been relatively small.").

[215] Crowther T. W., *et al.* (2016) *Quantifying global soil carbon losses in response to warming*, NATURE 540:104–108, 104 ("This provides strong empirical support for the idea that rising temperatures will stimulate the net loss of soil carbon to the atmosphere, driving a positive land carbon–climate feedback that could accelerate climate change.").

[216] Commane R., *et al.* (2017) *Carbon dioxide sources from Alaska driven by increasing early winter respiration from Arctic tundra*, PROC. NAT'L. ACAD. SCI. 114(21):5361–5366, 5365 ("We find that Alaska, overall, was a net source of carbon to the atmosphere during 2012–2014, when net emissions from tundra ecosystems overwhelmed a small net uptake from boreal forest ecosystems. Both ecosystems emitted large amounts of carbon in early winter. Our results suggest that October through December respiration has increased by about 73% over the past 41 y from organic carbon-rich soils on the North Slope of Alaska, correlated with increasing air temperatures. The ESMs used to forecast future carbon fluxes in the CMIP5 and IPCC studies did not represent early winter respiration, especially when soil temperatures hover near 0 ºC. Hence these assessments may underestimate the carbon release from arctic soils in response to warming climate.").

[217] Crowther T. W., *et al.* (2016) *Quantifying global soil carbon losses in response to warming*, NATURE 540:104–108, 106 ("Given that high-latitude regions have the largest standing soil C stocks and the fastest expected rates of warming, our results suggest that the overwhelming majority of warming-induced soil C losses are likely to occur in Arctic and subarctic regions. These high-latitude C losses considerably outweigh any minor changes expected in mid- and lower-latitude regions, providing further support for the idea of Arctic amplification of climate change feedbacks. These warming-induced soil C losses need to be considered in light of future changes in moisture stress and vegetation growth, which are also likely to increase disproportionately in high-latitude areas.").

[218] Crowther T. W., *et al.* (2016) *Quantifying global soil carbon losses in response to warming*, NATURE 540:104–108, 106 ("We extrapolated this relationship over the next 35 years to indicate how global soil C stocks might respond by 2050. The simple extrapolation of our empirical relationship suggests that 1 °C of warming over 35 years would drive the loss of 203 ± 161 PgC from the upper soil horizon. However, this approach implicitly assumes that the effects of a given amount of warming are never fully realized (that is, C stocks fall continuously even under a small amount of warming), so are likely to markedly overestimate total soil C losses (see Methods for details). As with mechanistic models, our assumptions about the rate at which soil C responds to warming will strongly

influence the magnitude of our predicted C losses. If we make the conservative assumption that the full effects of warming are fully realized within a year, then approximately 30 ± 30 PgC would be lost from the surface soil for 1°C of warming. Given that global average soil surface temperatures are projected to increase by around 2°C over the next 35 years under a business-as-usual emissions scenario, this extrapolation would suggest that warming could drive the net loss of approximately 55 ± 50 PgC from the upper soil horizon. If, as expected, this C entered the atmospheric pool, the atmospheric burden of CO_2 would increase by approximately 25 parts per million over this period.").

[219] Crowther T. W., *et al.* (2016) *Quantifying global soil carbon losses in response to warming*, NATURE 540:104–108, 104 ("Here we present a comprehensive analysis of warming-induced changes in soil carbon stocks by assembling data from 49 field experiments located across North America, Europe and Asia. We find that the effects of warming are contingent on the size of the initial soil carbon stock, with considerable losses occurring in high-latitude areas. … Our empirical relationship suggests that global soil carbon stocks in the upper soil horizons will fall by 30 ± 30 petagrams of carbon to 203 ± 161 petagrams of carbon under one degree of warming, depending on the rate at which the effects of warming are realized. Under the conservative assumption that the response of soil carbon to warming occurs within a year, a business-as-usual climate scenario would drive the loss of 55 ± 50 petagrams of carbon from the upper soil horizons by 2050. This value is around 12–17 per cent of the expected anthropogenic emissions over this period.").

[220] Chadburn S. E., *et al.* (2017) *An observation-based constraint on permafrost loss as a function of global warming*, NATURE CLIMATE CHANGE 7:340–344, 342 ("We estimate the committed permafrost loss over the whole twentieth century to be $3.4^{+2.2}_{-2.3}$ million km^2 (until 2003–2012). Some of this committed change will not yet be observable, because of the lag between the equilibrium and transient response. However, our estimate of permafrost sensitivity to warming is consistent with observations of changes in near-surface permafrost, which are expected to be much closer to equilibrium (see Supplementary Figs 6 and 7 and Supplementary Discussion). There may be longer-term transient effects, but these are relatively small (see Supplementary Fig. 2).").

[221] Biskaborn B. K., *et al.* (2019) *Permafrost is warming at a global scale*, NATURE COMMUNICATIONS 10(264):1–11, 1 ("Permafrost warming has the potential to amplify global climate change, because when frozen sediments thaw it unlocks soil organic carbon. Yet to date, no globally consistent assessment of permafrost temperature change has been compiled. Here we use a global data set of permafrost temperature time series from the Global Terrestrial Network for Permafrost to evaluate temperature change across permafrost regions for the period since the International Polar Year (2007–2009). During the reference decade between 2007 and 2016, ground temperature near the depth of zero annual amplitude in the continuous permafrost zone increased by 0.39±0.15°C. Over the same period, discontinuous permafrost warmed by 0.20 ± 0.10 °C. Permafrost in mountains warmed by 0.19 ± 0.05 °C and in Antarctica by 0.37 ± 0.10 °C. Globally, permafrost temperature increased by 0.29 ± 0.12 °C. The observed trend follows the Arctic amplification of air temperature increase in the Northern Hemisphere. In the discontinuous zone, however, ground warming occurred due to increased snow thickness while air temperature remained statistically unchanged.").

[222] Schaefer K., *et al.* (2011) *Amount and timing of permafrost carbon release in response to climate warming*, TELLUS SERIES B CHEMICAL & PHYSICAL METEOROLOGY 63(2):165–180, 165 ("Recent observations indicate widespread permafrost degradation in the Northern Hemisphere (Lemke et al., 2007). Permafrost temperatures at 20 m depth increased 2–3 ºC increase in the last two decades (Osterkamp, 2007). Permafrost temperatures at depths up to 20 m increased 0–2 ºC in Canada (Smith et al., 2004; Lemke et al., 2007), 0.3–2.8 ºC at depths up to 10 m in Siberian Arctic and sub-Arctic (Lemke et al., 2007), 0.2–0.5 ºC at 10 m depth on the Tibetan Plateau (Cheng and Wu, 2007; Lemke et al., 2007; Wu and Zhang, 2008).").

[223] Arctic Monitoring and Assessment Programme (AMAP) (2017) SNOW, WATER, ICE, AND PERMAFROST IN THE ARCTIC: SUMMARY FOR POLICYMAKERS, 4 ("Near-surface permafrost in the High Arctic and other very cold areas has warmed by more than 0.5°C since 2007–2009, and the layer of the ground that thaws in summer has deepened in most areas where permafrost is monitored.").

[224] Romanovsky V. E., *et al.* (2017) *Terrestrial Permafrost*, *in* ARCTIC REPORT CARD 2017 ("In 2016, record high temperatures at 20-m depth occurred at all permafrost observatories on the North Slope of Alaska except Deadhorse (Fig 2a) (Romanovsky et al., 2017). Since 2000, temperature at 20-m depth in this region has increased between 0.21° C and 0.66° C per decade (Fig. 2a; Table 1). Following the slight cooling of 2007–2013, permafrost temperatures increased in Interior Alaska at all sites, with especially strong increase at Birch Lake, associated with a new record high in 2016 for the entire 32 years of measurements (Fig. 2b; Table 1).").

[225] Arctic Monitoring and Assessment Programme (AMAP) (2017) ADAPTATION ACTIONS FOR A CHANGING ARCTIC: PERSPECTIVES FROM THE BARENTS AREA, 81 ("Active layer thickness (ALT) is more sensitive to short-term variations in climate than deeper ground. ALT records thus exhibit greater interannual variability, mainly in response to variations in summer temperature (e.g. Smith et al., 2009). Most regions where long-term ALT observations are available show an increase over the past five years (Romanovsky et al., 2015). The Russian European North has been characterized by almost monotonic thickening of the active layer over the past 15 years, reaching a maximum in 2012, but decreasing between 2012 and 2014. In the Nordic countries, records (1996–2013) indicate a general increase in ALT since 1999. Summer 2014 was particularly warm in the Nordic countries and contributed to the deepest active layer measured to date at some sites (Romanovsky et al., 2017).").

[226] Romanovsky V. E., *et al.* (2017) *Terrestrial Permafrost*, *in* ARCTIC REPORT CARD 2017 ("The average active-layer thickness (ALT; determined by mechanical probing and typically accurate to 0.5 cm) in 2016 for 20 North Slope sites was 0.52 m, which is 4 cm greater than the 1996–2016 average (Fig. 3). This value represents the 21-year maximum, which was previously achieved in 1998 and 2013 (Fig. 3). In the interior of Alaska ALT has on average increased by 0.14 m in 2016 compared to 2015 values. Three out of four Alaska Interior sites with 20 years of continuous observations reported absolute maximum ALT values in 2016. The previous maxima at these sites was achieved in 2015.").

[227] Arctic Monitoring and Assessment Programme (AMAP) (2017) ADAPTATION ACTIONS FOR A CHANGING ARCTIC: PERSPECTIVES FROM THE BARENTS AREA, 81 ("Active layer thickness (ALT) is more sensitive to short-term variations in climate than deeper ground. ALT records thus exhibit greater interannual variability, mainly in response to variations in summer temperature (e.g. Smith et al., 2009). Most regions where long-term ALT observations are available show an increase over the past five years (Romanovsky et al., 2015). The Russian European North has been characterized by almost monotonic thickening of the active layer over the past 15 years, reaching a maximum in 2012, but decreasing between 2012 and 2014. In the Nordic countries, records (1996–2013) indicate a general increase in ALT since 1999. Summer 2014 was particularly warm in the Nordic countries and contributed to the deepest active layer measured to date at some sites (Romanovsky et al., 2017).").

[228] Romanovsky V. E., *et al.* (2017) *Terrestrial Permafrost*, *in* ARCTIC REPORT CARD 2017 ("In West Siberia, the active-layer thickness increased by an average of 0.16 m in 2016, reaching 1.45 m, the highest recorded thickness in 20 years of observations. The previous maximum was 1.29 m in 2015. Similarly, the ALT in 2016 has substantially increased in Russian European North. Slight ALT increase in 2016 was observed in East Siberia and Chukotka (Russian Far East) (Fig. 3). In central Siberia ALT remained unchanged in 2016.").

[229] Tarnocai C., *et al.* (2009) *Soil organic carbon pools in the northern circumpolar permafrost region*, GLOBAL GEOCHEMICAL CYCLES 23(2):1–11, 1 ("The Northern Circumpolar Soil Carbon Database was developed in order to determine carbon pools in soils of the northern circumpolar permafrost region. The area of all soils in the northern permafrost region is approximately 18,782 × 10^3 km^2, or approximately 16% of the global soil area. In the northern permafrost region, organic soils (peatlands) and cryoturbated permafrost-affected mineral soils have the highest mean soil organic carbon contents (32.2–69.6 kg m^{-2}). Here we report a new estimate of the carbon pools in soils of the northern permafrost region, including deeper layers and pools not accounted for in previous analyses. Carbon pools were estimated to be 191.29 Pg for the 0–30 cm depth, 495.80 Pg for the 0–100 cm depth, and 1024.00 Pg for the 0–300 cm depth. Our estimate for the first meter of soil alone is about double that reported for this region in previous analyses. Carbon pools in layers deeper than 300 cm were estimated to be 407 Pg in yedoma deposits and 241 Pg in deltaic deposits. In total, the northern permafrost region contains approximately 1672 Pg of organic carbon, of which approximately 1466 Pg, or 88%, occurs in perennially frozen soils and deposits. This 1672 Pg of organic carbon would account for approximately 50% of the estimated global belowground organic carbon pool."); *see also* Hugelius G., *et al.* (2014) *Estimated stocks of circumpolar permafrost carbon with quantified uncertainty ranges and identified data gaps*, BIOGEOSCIENCES 11:6573–6593, 6574 ("Tarnocai et al. (2009) provided a total estimate of circumpolar SOC storage in soils (0–3 m depth), Yedoma and deltaic deposits of 1672 Pg, of which 1466 Pg is stored in permafrost terrain. This is about twice as much C as what is currently stored in the atmosphere (Houghton, 2007). While it is recognized that this pool of SOC stored in permafrost regions is large and potentially vulnerable to remobilization following permafrost thaw, estimates are poorly constrained and quantitative error estimates are lacking (Mishra et al., 2013). Tarnocai et al. (2009) assigned qualitative levels of confidence for different components of the permafrost region SOC stock estimate."); *and* World Bank & International Cryosphere Climate Initiative (ICCI) (2013) ON THIN ICE: HOW CUTTING POLLUTION CAN SLOW WARMING AND SAVE LIVES, 44 ("The earth's total permafrost holds an estimated 1,700 Gt of carbon, compared to 850 Gt currently in the atmosphere. Much of that below-ground carbon, however, exists at deep levels that will take more time to thaw and reach the surface.").

[230] Schaefer K., *et al.* (2011) *Amount and timing of permafrost carbon release in response to climate warming*, TELLUS SERIES B CHEMICAL & PHYSICAL METEOROLOGY 63(2):165–180, 165 ("By 2200, the PCF strength in terms of cumulative permafrost carbon flux to the atmosphere is 190 ± 64 Gt C. This estimate may be low because it does not account for amplified surface warming due to the PCF itself and excludes some discontinuous permafrost regions where SiBCASA did not simulate permafrost."); *see also* World Bank & International Cryosphere Climate Initiative (ICCI) (2013) ON THIN ICE: HOW CUTTING POLLUTION CAN SLOW WARMING AND SAVE LIVES, 44 ("Only about 190 Gt of CO_2 exists in the permafrost's top 30 centimeters and is considered most vulnerable to warming; even that relatively thin slice can increase the amount of carbon in the air by about 20 percent. Whatever percentage of permafrost emissions is emitted as methane (present under wet conditions) will contribute to near-term warming on potentially rapid scales because methane warms more powerfully than CO_2.").

[231] Schaefer K., *et al.* (2011) *Amount and timing of permafrost carbon release in response to climate warming*, TELLUS SERIES B CHEMICAL & PHYSICAL METEOROLOGY 63(2):165–180, 165 ("Permafrost regions in the Northern Hemisphere contain an estimated 1672 Gt of carbon (Tarnocai et al., 2009). Of this, 818 Gt of carbon is in the top 3 m of soil located in regions with permanently frozen soil or permafrost, 648 Gt is frozen in deposits known to extend below 3 m and 206 Gt is in the top 3 m of soil located in regions without permafrost (Tarnocai et al., 2009).").

[232] Vaughan D. G., *et al.* (2013) CHAPTER 4: OBSERVATIONS: CRYOSPHERE, *in* IPCC (2013) CLIMATE CHANGE 2013: THE PHYSICAL SCIENCE BASIS, Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 364 ("Significant permafrost degradation has been reported in the Russian European North (medium confidence). Warm permafrost with a thickness of 10 to 15 m thawed completely in the period 1975–2005 in the Vorkuta area (Oberman, 2008). And although boundaries between permafrost types are not easy to map, the southern permafrost boundary in this region is reported to have moved north by about 80 km and the boundary of continuous permafrost has moved north by 15 to 50 km (Oberman, 2008) (medium confidence). Taliks have also developed in relatively thick permafrost during the past several decades. In the Vorkuta region, the thickness of existing closed taliks increased by 0.6 to 6.7 m over the past 30 years (Romanovsky et al., 2010b). Permafrost thawing and talik formation has occurred in the Nadym and Urengoy regions in northwestern Russian (Drozdov et al., 2010). Long-term permafrost thawing has been reported around the city of Yakutsk, but this in this case, the thawing may have been caused mainly by forest fires or human disturbance (Fedorov and Konstantinov, 2008). Permafrost degradation has also been reported on the Qinghai-Xizang (Tibet) Plateau (Cheng and Wu, 2007; Li et al., 2008).").

[233] Abbott B. W., *et al.* (2016) *Biomass Offsets Little to None of Permafrost Carbon Release from Soils, Streams, and Wildfire: an Expert Assessment*, ENVTL. RESEARCH LETTERS 11(034014):1–13, 11 ("During the Paleocene–Eocene thermal maximum, high-latitude temperature warmed more than 10 °C, causing almost complete loss of permafrost and the mineralization of most permafrost soil organic matter (Bowen and Zachos 2010, DeConto et al 2012). More recently, the 2°C–4°C warming at high-latitudes during the early Holocene caused active-layer deepening throughout the permafrost region but did not trigger complete permafrost loss or widespread carbon release (French 1999, Schirrmeister et al 2002, Jorgenson et al 2013)…. There may have been a threshold between 4 °C and 10 °C high-latitude warming due to positive feedbacks such as a shift from a coniferous to a deciduous dominated system or an abrupt change in hydrology. If a tipping point does exist between 4 and 10 °C high-latitude warming, it would fall between scenarios RCP4.5 and RCP8.5, representing maximum atmospheric CO_2 of 650 ppm and 850 ppm, respectively (Moss et al 2010, Lawrence et al 2012). RCP4.5 is still widely accepted as politically and technically attainable, though it assumes global CO_2 emissions peak before 2050 and decrease by half by 2080 (Moss et al 2010).").

[234] Abbott B. W., *et al.* (2016) *Biomass Offsets Little to None of Permafrost Carbon Release from Soils, Streams, and Wildfire: an Expert Assessment*, ENVTL. RESEARCH LETTERS 11(034014):1–13, 11 ("During the Paleocene–Eocene thermal maximum, high-latitude temperature warmed more than 10 °C, causing almost complete loss of permafrost and the mineralization of most permafrost soil organic matter (Bowen and Zachos 2010, DeConto et al 2012). More recently, the 2°C–4°C warming at high-latitudes during the early Holocene caused active-layer deepening throughout the permafrost region but did not trigger complete permafrost loss or widespread carbon release (French 1999, Schirrmeister et al 2002, Jorgenson et al 2013)…. There may have been a threshold between 4 °C and 10 °C high-latitude warming due to positive feedbacks such as a shift from a coniferous to a deciduous dominated system or an abrupt change in hydrology. If a tipping point does exist between 4 and 10 °C high-latitude warming, it would fall between scenarios RCP4.5 and RCP8.5, representing maximum atmospheric CO_2 of 650 ppm and 850 ppm, respectively (Moss et al 2010, Lawrence et al 2012). RCP4.5 is still widely accepted as politically and technically attainable, though it assumes global CO_2 emissions peak before 2050 and decrease by half by 2080 (Moss et al 2010).").

[235] Schädel C., *et al.* (2016) *Potential carbon emissions dominated by carbon dioxide from thawed permafrost soils*, NATURE CLIMATE CHANGE 6:950–953, 950 ("Increasing temperatures in northern high latitudes are causing permafrost to thaw, making large amounts of previously frozen organic matter vulnerable to microbial decomposition. Permafrost thaw also creates a fragmented landscape of drier and wetter soil conditions that determine the amount and form (carbon dioxide (CO_2), or methane (CH_4)) of carbon (C) released to the atmosphere. The rate and form of C release control the magnitude of the permafrost C feedback, so their relative contribution with a warming climate remains unclear. … Here we show, using two separate meta-analyses, that a 10ºC increase in incubation temperature increased C release by a factor of 2.0 (95% confidence interval (CI), 1.8 to 2.2). Under aerobic incubation conditions, soils released 3.4 (95% CI, 2.2 to 5.2) times more C than under anaerobic conditions. Even when accounting for the higher heat trapping capacity of CH_4, soils released 2.3 (95% CI, 1.5 to 3.4) times more C under aerobic conditions. These results imply that permafrost ecosystems thawing under aerobic conditions and releasing CO_2 will strengthen the permafrost C feedback more than waterlogged systems releasing CO_2 and CH_4 for a given amount of C.").

[236] Schuur E. A. G., *et al.* (2015) *Climate Change and the Permafrost Carbon Feedback*, NATURE 520:171–179, 171 ("At the proposed rates, the observed and projected emissions of CH_4 and CO_2 from thawing permafrost are unlikely to cause abrupt climate change over a period of a few years to a decade. Instead, permafrost carbon emissions are likely to be felt over decades to centuries as northern regions warm, making climate change happen faster than we would expect on the basis of projected emissions from human activities alone.").

[237] Burke E. J., *et al.* (2013) *Estimating the Permafrost-Carbon Climate Response in the CMIP5 Climate Models Using a Simplified Approach*, J. CLIMATE 26:4897–4909, 4898 ("In general, the permafrost-carbon climate feedback is not yet included within coupled earth system general circulation models (GCMs)."); *see also* Schneider von Deimling T., *et al.* (2012) *Estimating the near-surface permafrost-carbon feedback on global warming*, BIOGEOSCIENCES 9:649–665, 650 ("Additional release of carbon from newly thawed permafrost, referred to as "permafrost-carbon feedback" in the following, would add to this land carbon feedback. At present, the release of additional carbon to the atmosphere as carbon dioxide or methane due to the thawing of permafrost and the subsequent decomposition of the soil organic carbon is not typically represented in carbon cycle models. For example, none of the carbon cycle models participating in C4MIP (Friedlingstein et al., 2006) included this feedback.").

[238] Stocker T. F., et al (2013) TECHNICAL SUMMARY, in IPCC (2013) CLIMATE CHANGE 2013: THE PHYSICAL SCIENCE BASIS, Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 103 ("Accounting for an unanticipated release of GHGs from permafrost or methane hydrates, not included in studies assessed here, would also reduce the anthropogenic CO_2 emissions compatible with a given temperature target. Requiring a higher likelihood of temperatures remaining below a given temperature target would further reduce the compatible emissions….").

[239] Hayes D. J., *et al.* (2014) *The impacts of recent permafrost thaw on land–atmosphere greenhouse gas exchange*, ENVTL. RESEARCH LETTERS 9(045005):1–12, 5 ("Over recent decades, our results show that active layer dynamics associated with permafrost thaw are causing the Pan-Arctic domain to become an increasing C source in both the continuous and discontinuous permafrost zones (figure 5).").

[240] Schaefer K., *et al.* (2011) *Amount and timing of permafrost carbon release in response to climate warming*, TELLUS SERIES B CHEMICAL & PHYSICAL METEOROLOGY 63(2):165–180, 165 ("We predict that the [permafrost carbon feedback (PCF)] will change the arctic from a carbon sink to a source after the mid-2020s and is strong enough to cancel 42–88% of the total global land sink. The thaw and decay of permafrost carbon is irreversible and accounting for the PCF will require larger reductions in fossil fuel emissions to reach a target atmospheric CO_2 concentration.").

[241] Parazoo N. C., *et al.* (2018) *Detecting the permafrost carbon feedback: talik formation and increased cold-season respiration as precursors to sink-to-source transitions*, CRYOSPHERE 12(1):123–144, 141 ("However, sustained warming over the next 300 years drives accelerated permafrost degradation and soil respiration, leading to widespread shifts in the C balance of Arctic ecosystems toward long-term net C source by the end of the 23rd century.").

[242] Parazoo N. C., *et al.* (2018) *Detecting the permafrost carbon feedback: talik formation and increased cold-season respiration as precursors to sink-to-source transitions*, CRYOSPHERE 12(1):123–144, 141 ("Also, 6.8 million km^2 of land impacted in Siberia and North America will produce an integrated C source of 90 Pg C by 2100 and 120 Pg C by 2200. Our projected permafrost C feedback is comparable to the contemporary land use and land use change contribution to the annual C cycle.").

[243] Lawrence D. M., *et al.* (2012) *Simulation of Present-Day and Future Permafrost and Seasonally Frozen Ground Conditions in CCSM4*, J. CLIMATE 25:2207–2225, 2207 ("The representation of permafrost and seasonally frozen ground and their projected twenty-first century trends is assessed in the Community Climate System Model, version 4 (CCSM4) and the Community Land Model version 4 (CLM4). The combined impact of advances in CLM and a better Arctic climate simulation, especially for air temperature, improve the permafrost simulation in CCSM4 compared to CCSM3. Present-day continuous plus discontinuous permafrost extent is comparable to that observed [12.5×10^6 versus $(11.8–14.6) \times 10^6$ km^2], but active layer thickness (ALT) is generally too thick and deep ground (.15 m) temperatures are too warm in CCSM4. Present-day seasonally frozen ground area is well simulated (47.5×10^6 versus 48.1×10^6 km^2). ALT and deep ground temperatures are much better simulated in offline CLM4 (i.e., forced with observed climate), which indicates that the remaining climate biases, particularly excessive high-latitude snowfall biases, degrade the CCSM4 permafrost simulation. Near-surface permafrost (NSP) and seasonally frozen ground (SFG) area are projected to decline substantially during the twenty-first century [representative concentration projections (RCPs); RCP8.5: NSP by 9.0×10^6 km^2, 72%, SFG by 7.1×10^6, 15%; RCP2.6: NSP by 4.1×10^6, 33%, SFG by 2.1×10^6, 4%]. The permafrost degradation rate is slower (2000–50) than in CCSM3 by ~35% because of the improved soil physics. Under the low RCP2.6 emissions pathway, permafrost state stabilizes by 2100, suggesting that permafrost related feedbacks could be minimized if greenhouse emissions could be reduced. The trajectory of permafrost degradation is affected by CCSM4 climate biases. In simulations with this climate bias ameliorated, permafrost degradation in RCP8.5 is lower by ~29%. Further reductions of Arctic climate biases will increase the reliability of permafrost projections and feedback studies in earth system models.").

[244] Abbott B. W., *et al.* (2016) *Biomass Offsets Little to None of Permafrost Carbon Release from Soils, Streams, and Wildfire: an Expert Assessment*, ENVTL. RESEARCH LETTERS 11(034014):1–13, 11 ("Our study highlights that Arctic and boreal biomass should not be counted on to offset permafrost carbon release and suggests that the permafrost region will become a carbon source to the atmosphere by 2100 regardless of warming scenario. Perhaps more importantly, our results indicate a 5-fold difference in emissions between the business as usual scenario (RCP8.5) and active reduction of human emissions (RCP2.6), suggesting that up to 85% of carbon release from the permafrost region can still be avoided, though the window of opportunity for keeping that carbon in the ground is rapidly closing.").

[245] Schneider von Deimling T., *et al.* (2012) *Estimating the near-surface permafrost-carbon feedback on global warming*, BIOGEOSCIENCES 9:649–665, 660 ("For lower scenarios, e.g. the mitigation scenario RCP3-PD, our results suggest that future warming is unlikely to increase Arctic temperatures enough to release a large fraction of the carbon stored in permafrost soils, although up to 22 % could be thawed already by 2100. If strong mitigation of emissions is pursued, it seems still possible to prevent the release of large fractions of this permafrost carbon over the coming centuries.").

[246] Schneider von Deimling T., *et al.* (2015) *Observation-based modelling of permafrost carbon fluxes with accounting for deep carbon deposits and thermokarst activity*, BIOGEOSCIENCES 12:3469–3488, 3470 ("However, the magnitude and timing of carbon fluxes as a consequence of permafrost degradation are highly uncertain. This is mainly due to incomplete observational knowledge of the amount of organic matter stored in permafrost deposits, of its quality and decomposability, as well as due to the challenge of modelling the full chain of processes from permafrost thaw to carbon release. Furthermore, conceptual and numerical permafrost landscape models also require suitable upscaling methods ranging from local to global scales, based on field-based knowledge of the surface characteristics, key processes and data collection of key parameters (Boike et al., 2012). The vulnerability of permafrost carbon and its fate when thawed will be strongly determined by various environmental controls (Grosse et al., 2011) such as soil type and soil moisture, which both affect soil thermal conductivity and therefore determine the timescale of heat penetration into the ground. Additionally, surface conditions such as organic-rich soil surface layers, vegetation cover and snow exert strong controls on subsurface temperatures by insulating the ground from surface air temperatures (Koven et al., 2013a).").

[247] Schaefer K., *et al.* (2011) *Amount and timing of permafrost carbon release in response to climate warming*, TELLUS SERIES B CHEMICAL & PHYSICAL METEOROLOGY 63(2):165–180, 166 ("Model projections predict increased permafrost degradation in the 21st century driven by surface warming, but these projections vary widely in the extent and degree of degradation. Zhang et al. (2008a,b) predict a 16–20% decrease in permafrost area in Canada between 2000 and 2100; Saito et al. (2007) predict a 40–57% reduction in the permafrost area in the Northern Hemisphere; Lawrence and Slater (2005) predict a 60–90% reduction and Lawrence et al. (2008) predict an 80–85% reduction. Projections of the increase in ALT are equally broad, ranging from 41% to 100% (Anisimov, 2007; Saito et al., 2007; Sushama et al., 2007; Zhang et al., 2008a,b). Although these projections vary widely on the exact

amount of permafrost degradation, there is agreement that the areal extent of permafrost will decrease and the active layer will deepen.”).

[248] Alexander L. V., *et al.* (2013) Summary for Policymakers, *in* IPCC (2013) Climate Change 2013: The Physical Science Basis, Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 25 (“It is virtually certain that near-surface permafrost extent at high northern latitudes will be reduced as global mean surface temperature increases. By the end of the 21st century, the area of permafrost near the surface (upper 3.5 m) is projected to decrease by between 37% (RCP2.6) to 81% (RCP8.5) for the model average (medium confidence).”); *see also* Collins M., *et al.* (2013) Chapter 12: Long-Term Climate Change: Projections, Commitments, and Irreversibility, *in* IPCC (2013) Climate Change 2013: The Physical Science Basis, Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 1092, Figure 12.33.

[249] Schneider von Deimling T., *et al.* (2012) *Estimating the near-surface permafrost-carbon feedback on global warming*, Biogeosciences 9:649–665, 657 (“Our global-mean temperature simulations of the RCP scenarios, once including the permafrost module and once excluding it, indicate that the median warming by 2100 is not substantially altered. If we accounted for rather high rates of permafrost thaw as modeled by Lawrence et al. (2008a) and Schaefer et al. (2011) we expect to infer a non-negligible warming contribution by 2100 from permafrost carbon for the high anthropogenic emission scenarios. For the mitigation scenario RCP3-PD, our results suggest that permafrost-carbon feedbacks add negligibly to the warming. For the high RCP8.5 scenario, permafrost-carbon feedbacks can trigger additional global-mean temperature increase of about 0.1ºC (0.04–0.23ºC) by 2100, further increasing to 0.38 C (0.18–0.78ºC) by 2200 and 0.42ºC (0.24–0.78ºC) in 2300 (see Table 2 and Fig. 3f). The intermediate RCP scenarios imply intermediate permafrost feedbacks, roughly proportional to their radiative forcing levels (see Table 2).”).

[250] Arctic Monitoring and Assessment Programme (AMAP) (2017) Snow, Water, Ice, and Permafrost in the Arctic: Summary for Policymakers, 12 (“The area of near-surface permafrost in the Northern Hemisphere is projected to decline by 20% relative to today’s area by 2040, and could be reduced by as much as two-thirds by 2080 under a scenario of high greenhouse gas emissions. Impacts will vary widely at regional and local scales, but local effects are difficult to project given the lack of fine-scale detail in models.”).

[251] Chadburn S. E., *et al.* (2017) *An observation-based constraint on permafrost loss as a function of global warming*, Nature Climate Change 7:340–344, 341 (“Using our approach, the loss of permafrost under stabilization, as a function of the global mean warming, is $4.0^{+1.0}_{-1.1}$ million km^2 $ºC^{-1}$ (note that all uncertainties are quoted at 1σ level). Under a 1.5 ºC stabilization scenario, $4.8^{+2.0}_{-2.2}$ million km^2 of permafrost would be lost compared with the 1960–1990 baseline (corresponding to the IPA map, Fig. 1b), and under a 2ºC stabilization we would lose $6.6^{+2.0}_{-2.2}$ million km^2, over 40% of the present-day permafrost area. Therefore, stabilizing at 1.5 ºC rather than 2 ºC could potentially prevent approximately 2 million km^2 of permafrost from thawing. The loss of permafrost with warming is shown on Fig. 3 for a wide range of scenarios. Our results indicate that for the high warming scenarios (5 or 6 ºC above pre-industrial—similar to the warming in RCP8.5 by 2100), the vast majority of permafrost will thaw, leaving only 0.3–3.1 million km^2 under 5 ºC of warming and 0.0–1.5 million km^2 under 6 ºC.”).

[252] Schaefer K., *et al.* (2014) *The Impact of the Permafrost Carbon Feedback on Global Climate*, Envtl Research Letters 9:1–9, 7 (“Available estimates of the PCF indicate 120 ± 85 Gt of carbon emissions from thawing permafrost by 2100. This is equivalent to 5.7 ± 4.0% of total anthropogenic emissions for the RCP8.5 scenario and would increase global temperatures by 0.29 ± 0.21 °C or 7.8 ± 5.7%. For RCP4.5, the scenario closest to the 2 °C warming target for the climate change treaty, the range of cumulative emissions in 2100 from thawing permafrost decreases to between 27 and 100 Gt C and the impact on temperature to between 0.05 and 0.15 °C, but the relative fraction of permafrost to total emissions increases to between 3% and 11%. Projections indicate 60% of the permafrost emissions will occur after 2100, indicating that not accounting for permafrost emissions risks overshooting the 2°C warming target. AR5 climate projections, and any emissions targets based on those projections, do not include the PCF. Consequently, we recommend the IPCC commission a special assessment focusing on the PCF and its impact on global climate to support treaty negotiation.”).

[253] Schneider von Deimling T., *et al.* (2012) *Estimating the near-surface permafrost-carbon feedback on global warming*, Biogeosciences 9:649–665, 649 (“Here, we couple a new permafrost module to a reduced complexity carbon-cycle climate model, which allows us to perform a large ensemble of simulations. The ensemble is designed to span the uncertainties listed above and thereby the results provide an estimate of the potential strength of the

feedback from newly thawed permafrost carbon. For the high CO_2 concentration scenario (RCP8.5), 33–114 GtC (giga tons of Carbon) are released by 2100 (68% uncertainty range). This leads to an additional warming of 0.04–0.23 ºC. Though projected 21st century permafrost carbon emissions are relatively modest, ongoing permafrost thaw and slow but steady soil carbon decomposition means that, by 2300, about half of the potentially vulnerable permafrost carbon stock in the upper 3 m of soil layer (600–1000 GtC) could be released as CO_2, with an extra 1–4 % being released as methane. Our results also suggest that mitigation action in line with the lower scenario RCP3-PD could contain Arctic temperature increase sufficiently that thawing of the permafrost area is limited to 9–23 % and the permafrost-carbon induced temperature increase does not exceed 0.04–0.16 ºC by 2300.").

[254] Burke E. J., *et al.* (2012) *Uncertainties in the global temperature change caused by carbon release from permafrost thawing*, CRYOSPHERE 6:1063–1076, 1069 ("As might be expected from the increase in the simulated global mean temperature, the permafrost extent decreases and the active layer deepens over the 21st century for each of the RCP scenarios. By the 2080s the simulated near-surface extent has decreased to 17.6 million km^2 for RCP2.6, 14.1 million km^2 for RCP4.5, 13.6 million km^2 for RCP6.0, and 8.5 million km^2 for RCP8.5. This represents a loss of between 25 % and 65 %, depending on the scenario. This loss is slightly less than that projected by Lawrence and Slater (2005) but larger than that projected by Schaefer et al. (2011).").

[255] Arctic Monitoring and Assessment Programme (AMAP) (2017) ADAPTATION ACTIONS FOR A CHANGING ARCTIC: PERSPECTIVES FROM THE BARENTS AREA, 80 ("The changes taking place in permafrost areas under a warming climate are having various impacts. Thawing permafrost has major consequences for buildings, infrastructure and transport networks designed to be supported by frozen ground. For example, roads can be badly damaged when ice within the soil melts and the land subsides. Another effect of thawing permafrost is the release of methane and the reinforcement of the global greenhouse effect. Thawing permafrost can also increase the risk of erosion and landslides if the frozen water in the soil has been acting as a glue.").

[256] Hjort J., *et al.* (2018) *Degrading permafrost puts Arctic infrastructure at risk by mid-century*, NATURE COMMUNICATIONS 9(5147):1–9, 1 ("Degradation of near-surface permafrost can pose a serious threat to the utilization of natural resources, and to the sustainable development of Arctic communities. 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.").

[257] Arctic Monitoring and Assessment Programme (AMAP) (2017) SNOW, WATER, ICE, AND PERMAFROST IN THE ARCTIC: SUMMARY FOR POLICYMAKERS, 14 ("Communities and infrastructure built on frozen soils are significantly affected by thawing permafrost, one of the most economically costly impacts of climate change in the Arctic. The bearing capacity of building foundations has declined by 40–50% in some Siberian settlements since the 1960s, and the vast Bovanenkovo gas field in western Siberia has seen a recent increase in landslides related to thawing permafrost. Thawing permafrost may also contaminate freshwater resources when previously frozen industrial and municipal waste is released.").

[258] Hope C. & Schaefer K. (2016) *Economic Impacts of Carbon Dioxide and Methane Released from Thawing Permafrost*, NATURE CLIMATE CHANGE 6:56–59, 56–57 ("Economic impacts are those that are included directly in gross domestic product (GDP), such as agricultural losses and air-conditioning costs; non-economic impacts are those that are not included directly in GDP, such as human health and ecosystem impacts. For clarity we collect all these impacts together under the description 'economic' in this paper. Thawing permafrost could also cause additional economic losses, as it could damage infrastructure and the foundations of buildings; this is not included in these calculations.… The median value is US$18 trillion, but the long right tail gives a mean value of US$43 trillion, with US$33 trillion coming from the emissions of CO_2, US$8 trillion from the emissions of CH_4, and the remainder from the nonlinear interactions between them. The standard error of this mean value from 100,000 runs is about US$2 trillion. For comparison, the gross world product under the A1B scenario is US$67 trillion in 2010 and US$805 trillion in 2100.").

[259] Kopp R. E., *et al.* (2016) *Temperature-driven global sea-level variability in the Common Era*, PROC. NAT'L. ACAD. SCI. 113(11):E1434–E1441, E1434 ("We assess the relationship between temperature and global sea-level (GSL) variability over the Common Era through a statistical metaanalysis of proxy relative sea-level reconstructions and tide gauge data. GSL rose at 0.1 ± 0.1 mm/y (2σ) over 0–700 CE. A GSL fall of 0.2 ± 0.2 mm/y over 1000–1400 CE is associated with ~0.2 °C global mean cooling. A significant GSL acceleration began in the 19th century

and yielded a 20th century rise that is extremely likely (probability P ≥ 0.95) faster than during any of the previous 27 centuries. A semiempirical model calibrated against the GSL reconstruction indicates that, in the absence of anthropogenic climate change, it is extremely likely (P = 0.95) that 20th century GSL would have risen by less than 51% of the observed 13.8 ± 1.5 cm. The new semiempirical model largely reconciles previous differences between semiempirical 21st century GSL projections and the process model-based projections summarized in the Intergovernmental Panel on Climate Change's Fifth Assessment Report."); *and* Strauss B. H., *et al.* (2015) *Carbon choices determine US cities committed to futures below sea level*, PROC. NAT'L. ACAD. SCI. 112(44):13508–13513, 13509 ("In this baseline case we find that cumulative emissions through 2015 already have locked in 1.6 m (0–3.7 m) of global SLR relative to the present level.").

[260] Pattyn F., *et al.* (2018) *The Greenland and Antarctic ice sheets under 1.5 ºC global warming*, NATURE CLIMATE CHANGE 8:1053–1061, 1053 ("Even if anthropogenic warming were constrained to less than 2 °C above pre-industrial, the Greenland and Antarctic ice sheets will continue to lose mass this century, with rates similar to those observed over the past decade. However, nonlinear responses cannot be excluded, which may lead to larger rates of mass loss. Furthermore, large uncertainties in future projections still remain, pertaining to knowledge gaps in atmospheric (Greenland) and oceanic (Antarctica) forcing. On millennial timescales, both ice sheets have tipping points at or slightly above the 1.5–2.0 °C threshold; for Greenland, this may lead to irreversible mass loss due to the surface mass balance–elevation feedback, whereas for Antarctica, this could result in a collapse of major drainage basins due to ice-shelf weakening.").

[261] Tedesco M., *et al.* (2016) *Greenland Ice Sheet*, *in* ARCTIC REPORT CARD ("The Greenland ice sheet plays a crucial role globally and locally, impacting the surface energy budget and climate and weather and contributing to current and future sea level rise. Estimates of the spatial extent of surface melt across the Greenland ice sheet (GrIS), over the period 1979 to 2016, are derived from brightness temperatures measured by the Special Sensor Microwave Imager/Sounder passive microwave radiometer (e.g., Mote 2007, Tedesco et al. 2013). Though 2016 was not a record-breaking year in terms of melt extent and duration, it extends the overall increasing melting trend. The updated trend for melt extent over the period 1979–2016 over the whole Greenland ice sheet is +15,824 km^2/yr.").

[262] Trusel L. D., *et al.* (2018) *Nonlinear rise in Greenland runoff in response to post-industrial Arctic warming*, NATURE 564:104–108, 106 ("Our reconstruction quantifies the exceptional magnitude of present- day melt and runoff relative to the last several centuries. Their rapid intensification over the last two decades also illustrates a clear non- linear melt–temperature relationship (Fig. 4c; Methods). Similar late-twentieth-century melt acceleration was found using records from an Antarctic Peninsula ice core, and attributed to a nonlinear response of melting to climate warming more broadly across Antarctica, owing largely to the melt–albedo positive feedback. At all of our core sites, 2012 melt was more intense than any other year according to two distinct reanalysis-forced regional climate models that extend back to 1958 and 1979 (Fig. 4c).").

[263] Tedesco M., *et al.* (2016) *The darkening of the Greenland ice sheet: trends, drivers, and projections (1981–2100)*, THE CRYOSPHERE 10:477–496, 478 ("The presence of LAI such as soot (black carbon, BC), dust, organic matter, algae, and other biological material in snow or ice also reduces the albedo, mostly in the visible and ultraviolet regions (Warren, 1982). Such impurities are deposited through dry and wet deposition, and their mixing ratios are enhanced through snow water loss in sublimation and melting (Conway et al., 1996; Flanner et al., 2007; Doherty et al., 2013). Besides grain growth and LAI, another cause of albedo reduction over the GrIS is the exposure of bare ice: once layers of snow or firn are removed through ablation, the exposure of the underlying bare ice will further reduce surface albedo, as does the presence of melt pools on the ice surface (e.g. Tedesco et al., 2011).").

[264] Pattyn F., *et al.* (2018) *The Greenland and Antarctic ice sheets under 1.5 ºC global warming*, NATURE CLIMATE CHANGE 8:1053–1061, 1054 ("A decrease in SMB lowers the ice-sheet surface, which in turn lowers SMB because at lower elevations, near-surface air temperature is generally higher. Additional SMB changes due to the SMB–surface elevation feedback are small for limited warming: in a coupled SMB–ice dynamical simulation, the feedback contributes 11% to the GrIS runoff rate in an RCP2.6 scenario, or ~3 mm of additional SLR by 2100.").

[265] Pattyn F., *et al.* (2018) *The Greenland and Antarctic ice sheets under 1.5 ºC global warming*, NATURE CLIMATE CHANGE 8:1053–1061, 1056 ("The AIS has been losing mass since the mid-1990s, contributing 0.15–0.46 mm yr^{-1} s.l.e. on average between 1992 and 2017, accelerating to 0.49–0.73 mm yr^{-1} between 2012 and 2017. Observations over the past five years show that mass loss mainly occurs in the Antarctic Peninsula and West Antarctica (0.42–0.65 mm yr^{-1} s.l.e.), with no significant contribution from East Antarctica (−0.01–0.16 mm yr^{-1} s.l.e.). The mass loss from the West Antarctic Ice Sheet (WAIS) is primarily caused by the acceleration of outlet glaciers in the Amundsen Sea Embayment (ASE), where the ice discharge of large outlet glaciers such as the Pine Island and Thwaites glaciers increased threefold since the early 1990s. However, this ASE mass loss is not a recent

phenomenon, as ocean sediment records indicate that Pine Island Glacier experienced grounding-line retreat since approximately the 1940s."); *and* Greenbaum J. S., *et al.* (2015) *Ocean access to a cavity beneath Totten Glacier in East Antarctica*, NATURE GEOSCIENCE 8:294–298, 297 ("[W]e expect the water column thickness over the trough to increase by several metres per year to maintain hydrostatic equilibrium if thinning trends continue. This could allow additional exchange between the TGIS and the ocean, accelerate ice-shelf thinning, and allow grounded ice to accelerate towards the coast. The availability of MCDW and recent accelerated mass loss support the idea that the behaviour of Totten Glacier is an East Antarctic analogue to ocean-driven retreat underway in the West Antarctic Ice Sheet (WAIS). The global sea level potential of 3.5 m flowing through Totten Glacier alone is of similar magnitude to the entire probable contribution of the WAIS. As with the WAIS, much of the broader drainage basin accessible to a retreating Totten Glacier is grounded below sea level, with a potential contribution of 5.1 m, so instabilities from ice–ocean interaction in East Antarctica could have significant global consequences.").

[266] Smith J. A., *et al.* (2017) *Sub-ice-shelf sediments record history of twentieth-century retreat of Pine Island Glacier*, NATURE 541:77–80, 77 ("Over the past 40 years, glaciers flowing into the Amundsen Sea sector of the ice sheet have thinned at an accelerating rate, and several numerical models suggest that unstable and irreversible retreat of the grounding line—which marks the boundary between grounded ice and floating ice shelf— is underway.").

[267] Alley K. E., *et al.* (2016) *Impacts of warm water on Antarctic ice shelf stability through basal channel formation*, NATURE GEOSCIENCE 9:290–293, 292 ("Our observations and statistical correlations between channel density, basal-melt rate, and grounding line depth suggest that ocean-sourced and grounding-line-sourced basal channel formation is primarily driven by [Circumpolar Deep Water], and that the channels can evolve on short timescales. The presence and growth of channels can cause structural ice-shelf-weakening along already-vulnerable shear zones, which leads us to suggest a possible future scenario in which ice-shelf basal channels could lead to large-scale destabilization through the reduction of ice-shelf back stress. With increased access of warm water beneath ice shelves and further incision of channels along shear margins, a tipping point could be reached where an ice shelf margin becomes disrupted enough to lead to increased calving, reduced ice shelf area, increased grounded ice flux, and accelerated sea-level rise. Although basal melting at the grounding line has already been shown to lead to increased ice flux, the implied additional mechanism of shear-margin weakening by basal channels could further accelerate grounded ice loss, a feedback that requires significant further exploration.").

[268] Favier L., *et al.* (2014) *Retreat of Pine Island Glacier controlled by marine ice-sheet instability*, NATURE CLIMATE CHANGE 4:117–121, 117 ("In recent years, the grounding line, which separates the grounded ice sheet from the floating ice shelf, has retreated by tens of kilometres. At present, the grounding line is crossing a retrograde bedrock slope that lies well below sea level, raising the possibility that the glacier is susceptible to the marine ice-sheet instability mechanism. Here, using three state-of-the-art ice-flow models, we show that Pine Island Glacier's grounding line is probably engaged in an unstable 40km retreat. The associated mass loss increases substantially over the course of our simulations from the average value of 20 Gt yr^{-1} observed for the 1992–2011 period, up to and above 100 Gt yr^{-1}, equivalent to 3.5–10 mm eustatic sea-level rise over the following 20 years. Mass loss remains elevated from then on, ranging from 60 to 120 Gt yr^{-1}.").

[269] DeConto R. M. & Pollard D. (2016) *Contribution of Antarctica to past and future sea-level rise*, NATURE 531:591–597, 593 ("The RCP scenarios (Fig. 4) produce a wide range of future Antarctic contributions to sea level, with RCP2.6 producing almost no net change by 2100, and only 20 cm by 2500. Conversely, RCP4.5 causes almost complete WAIS collapse within the next five hundred years, primarily owing to the retreat of Thwaites Glacier into the deep WAIS interior. … In RCP4.5, GMSL rise is 32 cm by 2100, but subsequent retreat of the WAIS interior, followed by the fringes of the Wilkes Basin and the Totten Glacier/Law Dome sector of the Aurora Basin produces 5 m of GMSL rise by 2500.").

[270] Li X., *et al.* (2016) *Ice flow dynamics and mass loss of Totten Glacier, East Antarctica, from 1989 to 2015*, GEOPHYSICAL RESEARCH LETTERS 43:6366–6373, 6371 ("We attribute the changes in ice dynamics to oceanic forcing because field observations have shown the presence of mCDW on the continental shelf near Totten [Bindoff et al., 2000; Williams et al., 2011]. Warm mCDW fuels high melt rates in this area, and a change in ocean temperature is the most likely explanation for the observed change in ice dynamics. Sea floor bathymetry from gravity inversion reveals the presence of a valley crossing the main sill in front of the glacier that is deeper than the thermocline depth [Blankenship et al., 2015]. This valley may allow access of warm modified Circumpolar Deep Water (mCDW) to the sub–ice shelf cavity and induce rapid ice shelf melting. The main stream is grounded >2300 m below sea level at the grounding line, which is the deepest part of the sub–ice shelf cavity. Ice shelf melt rates are expected to be highest in this region due to the pressure dependence of the freezing point of seawater. …Grounding line retreat has also been observed [Li et al., 2015]. The reanalysis temperature data from ECCO2 solution indicate three periods of warming/cooling of the subsurface water (450 – 600 m depth) on the continental shelf, which agree

with periods of acceleration/deceleration of the glacier. If this is correct, this indicates a significant sensitivity of the glacier to ocean temperature, which is consistent with the presence of an ice plain in the grounding line region [Li et al., 2015]. Coastal polynya activities can cause short-term variability in subglacial melt rates by modulating mCDW access into the sub – ice shelf cavity [Khazendar et al., 2013; Gwyther et al., 2014].").

[271] Arctic Monitoring and Assessment Programme (AMAP) (2017) SNOW, WATER, ICE, AND PERMAFROST IN THE ARCTIC: SUMMARY FOR POLICYMAKERS, 4 (*see* figure).

[272] Arctic Monitoring and Assessment Programme (AMAP) (2017) SNOW, WATER, ICE, AND PERMAFROST IN THE ARCTIC: SUMMARY FOR POLICYMAKERS, 4 (*see* figure).

[273] Box J. E., *et al.* (2018) *Global sea-level contribution from Arctic land ice: 1971–2017*, ENVTL. RESEARCH LETTERS 13(125012):1–11, 1 ("We contend that our estimate represents the most accurate Arctic land ice mass balance assessment so far available before the 1992 start of satellite altimetry. We estimate the 1971–2017 eustatic sea-level contribution from land ice north of ~55 °N to be 23.0 ± 12.3 mm sea-level equivalent (SLE). In all regions, the cumulative sea-level rise curves exhibit an acceleration, starting especially after 1988. Greenland is the source of 46% of the Arctic sea-level rise contribution (10.6 ± 7.3 mm), followed by Alaska (5.7 ± 2.2 mm), Arctic Canada (3.2 ± 0.7 mm) and the Russian High Arctic (1.5 ± 0.4 mm).").

[274] Arctic Monitoring and Assessment Programme (AMAP) (2017) SNOW, WATER, ICE, AND PERMAFROST IN THE ARCTIC: SUMMARY FOR POLICYMAKERS, 4 (*see* figure).

[275] Arctic Monitoring and Assessment Programme (AMAP) (2017) SNOW, WATER, ICE, AND PERMAFROST IN THE ARCTIC: SUMMARY FOR POLICYMAKERS, 4 (*see* figure).

[276] Dutton A., *et al.* (2015) *Sea-level rise due to polar ice-sheet mass loss during past warm periods*, SCIENCE 349(6244):153, 153 ("Although thermal expansion of seawater and melting of mountain glaciers have dominated global mean sea level (GMSL) rise over the last century, mass loss from the Greenland and Antarctic ice sheets is expected to exceed other contributions to GMSL rise under future warming.").

[277] Kopp R. E., *et al.* (2016) *Temperature-driven global sea-level variability in the Common Era*, PROC. NAT'L. ACAD. SCI. 113(11):E1434–E1441, E1434 ("We assess the relationship between temperature and global sea-level (GSL) variability over the Common Era through a statistical metaanalysis of proxy relative sea-level reconstructions and tide gauge data. GSL rose at 0.1 ± 0.1 mm/y (2σ) over 0–700 CE. A GSL fall of 0.2 ± 0.2 mm/y over 1000–1400 CE is associated with ~0.2 °C global mean cooling. A significant GSL acceleration began in the 19th century and yielded a 20th century rise that is extremely likely (probability P ≥ 0.95) faster than during any of the previous 27 centuries. A semiempirical model calibrated against the GSL reconstruction indicates that, in the absence of anthropogenic climate change, it is extremely likely (P = 0.95) that 20th century GSL would have risen by less than 51% of the observed 13.8 ± 1.5 cm. The new semiempirical model largely reconciles previous differences between semiempirical 21st century GSL projections and the process model-based projections summarized in the Intergovernmental Panel on Climate Change's Fifth Assessment Report.").

[278] Intergovernmental Panel on Climate Change (IPCC) (2014) CLIMATE CHANGE 2014: SYNTHESIS REPORT, Contribution of Working Groups I, II, and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 42 ("Over the period 1901–2010, global mean sea level rose by 0.19 [0.17 to 0.21] m (Figure 1.1). The rate of sea level rise since the mid-19th century has been larger than the mean rate during the previous two millennia (*high confidence*).").

[279] Strauss B. H., *et al.* (2015) *Carbon choices determine US cities committed to futures below sea level*, PROC. NAT'L. ACAD. SCI. 112(44):13508–13513, 13509 ("In this baseline case we find that cumulative emissions through 2015 already have locked in 1.6 m (0–3.7 m) of global SLR relative to the present level.").

[280] Strauss B. H., *et al.* (2015) *Carbon choices determine US cities committed to futures below sea level*, PROC. NAT'L. ACAD. SCI. 112(44):13508–13513, 13509 ("Sea-level commitment rises to 2.2 m (0.4–4.0 m) after factoring in future emissions implied by the current energy infrastructure and reaches medians of 2.4 or 7.1 m by the end of the century under RCP 2.6 or 8.5, respectively.").

[281] Bittermann K., *et al.* (2017) *Global mean sea-level rise in a world agreed upon in Paris*, ENVTL. RESEARCH LETTERS 12(124010):1–9, 5–6 ("Projections from our semi-empirical model show that amount and rate of future GMSL rise is dependent upon temperature scenarios, even where the scenarios under investigation meet the ambitious goals of the Paris Agreement. Subsampling RCP 2.6 to lower the likelihood of exceeding 1.5 ºC by 2150 CE from 54% to 5%, without overshoot, makes a ~10 cm difference in the median GMSL projection. Under the idealized trajectories, stabilizing temperature at 1.5 ºC above pre-industrial results in a GMSL change that is smaller (by 17 (14–21) cm in 2150) and slower (for the maximum rate, by 1.9 (1.4–2.6) mm yr^{-1}) than stabilization at 2.0 ºC. An overshoot to 2 ºC and a subsequent decline to 1.5 ºC also causes less GMSL rise (12 (10–16) cm) by 2150 CE than stabilization at 2 ºC. If stabilization at 2 ºC occurred in 2080 CE, then the maximum rate of GMSL rise is

2.6 (2.0–4.0) mm yr^{-1} slower than if temperature were to stabilize in 2030 CE. These results indicate that an immediate reduction in the rate of warming and a low stabilization temperature, even if overshot transiently, will result in a considerable reduction in the amount and rate of GMSL rise that global coastlines and coastal communities will experience during the 21st century and beyond.").

[282] Arctic Monitoring and Assessment Programme (AMAP) (2017) SNOW, WATER, ICE, AND PERMAFROST IN THE ARCTIC: SUMMARY FOR POLICYMAKERS, 6 ("Efforts to control greenhouse gas emissions can have a major impact on sea-level rise after mid-century. For example, a scenario roughly consistent with the Paris Agreement would reduce end-of-century sea-level rise by 43% compared with that projected to occur under a business-as-usual emissions scenario.").

[283] Arctic Monitoring and Assessment Programme (AMAP) (2017) SNOW, WATER, ICE, AND PERMAFROST IN THE ARCTIC: SUMMARY FOR POLICYMAKERS, 12 ("The SWIPA analysis estimates that when all sources of sea-level rise are considered (not just those from the Arctic), the rise in global sea level by 2100 would be at least 52 cm for a greenhouse gas reduction scenario and 74 cm for a business-as-usual scenario. These estimates are almost double the minimum estimates made by the IPCC in 2013.").

[284] Rasmussen D. J., *et al.* (2018) *Extreme sea level implications of 1.5 ºC, 2.0 ºC, and 2.5 ºC temperature stabilization targets in the 21st and 22nd centuries*, ENVTL. RESEARCH LETTERS 13(034040):1–12, 2 ("Under stabilized GMST, GMSL is expected to continue to rise for centuries, due to the long residence time of anthropogenic CO_2, the thermal inertia of the ocean, and the slow response of large ice sheets to forcing (Clark *et al* 2016, Levermann *et al* 2013, Held *et al* 2010). For instance, Schaeffer *et al* (2012) found that a 2.0 ºC GMST stabilization would lead to a GMSL rise (relative to 2000) of 0.8 m by 2100 and >2.5 m by 2300, but if the GMST increase were held below 1.5 ºC, GMSL rise at the end of the 23rd century would be limited to ~1.5m. These findings suggest that selection of climate policy goals could have critical long-term consequences for the impacts of future SLR and coastal floods (Clark *et al* 2016)."); *see also* Wigley T. M. L. (2018) *The Paris warming targets: emissions requirements and sea level consequences*, CLIMATIC CHANGE 147:31–45, 37 ("From Fig. 3, it is clear that CO_2 concentration stabilization at 350 ppm or above fails to lead to anything like sea level stabilization. Sea level rise for WRE350 reaches about 80 cm by 2300 (relative to 2000) and is still rising then at about 14 cm per century. WRE250 comes closer to stabilizing sea level, but still leads to at least an additional 46 cm sea level rise by 2300 relative to 2000.").

[285] Rasmussen D. J., *et al.* (2018) *Extreme sea level implications of 1.5 ºC, 2.0 ºC, and 2.5 ºC temperature stabilization targets in the 21st and 22nd centuries*, ENVTL. RESEARCH LETTERS 13(034040):1–12, 2 ("The advantages and disadvantages of each GMST target as they relate to coastal floods and ESLs have not been quantified. This is critical, as >625 million people currently live in coastal zones with <10 m of elevation, and population growth is expected in these areas (Neumann *et al* 2015). Examining the short- and long-term ESL implications of 1.5 ºC and 2.0 ºC GMST stabilization scenarios, as others have recently done for other climate impacts (e.g. Schleussner *et al* 2016a, 2016b, Mitchell *et al* 2017, Mohammed *et al* 2017), may better inform the policy debate regarding the selection of GMST goals.").

[286] Rasmussen D. J., *et al.* (2018) *Extreme sea level implications of 1.5 ºC, 2.0 ºC, and 2.5 ºC temperature stabilization targets in the 21st and 22nd centuries*, ENVTL. RESEARCH LETTERS 13(034040):1–12, 8–9 ("Sea-level rise will amplify the frequency of all ESL events, but depending on the shape of the GPD, the frequency of some ESL events may amplify more than others (Buchanan *et al* 2017). For example, by 2100 under a 2.0 ºC and 1.5 ºC GMST stabilization, respectively, median local SLR for Kushimoto, Japan is projected to be 79 cm (*likely* 58–103 cm) and 70 cm (*likely* 52–92 cm), increasing the respective number of historical 10 year ESL events from 0.1/year, on average, to 146/year (AF of 1462) and 128/year (AF of 1277), on average. However, for the same amount of local SLR, the historical number of expected 500 year ESL events for Kushimoto increases from 0.002/year to 83/year (2.0 ºC; AF of 41479) and 57/year (1.5 ºC; AF of 28 645). When the shape of the return curve is log-linear (as occurs when the shape parameter (ξ) is zero), ESL events amplify equally across return periods. For example, by 2100, under 1.5 ºC, 2.0 ºC, and 2.5 ºC GMST stabilization, respectively, Cuxhaven, Germany is projected to have median local SLR of 43 cm (*likely* 26–65 cm), 53 cm (*likely* 29–82 cm) and 51 cm (*likely* 34–71 cm). The historical 500 year ESL event is projected to become as or more frequent than the historical 100 year ESL event for all scenarios: 0.01/year (1.5 ºC; AF of 5.6), 0.03/year (2.0 ºC; AF of 13.5), and 0.01/year (2.5 ºC; AF of 6.5).").

[287] Storlazzi C. D., *et al.* (2018) *Most atolls will be uninhabitable by the mid-21st century because of sea-level rise exacerbating wave-driven flooding*, SCIENCE ADVANCES 4(eaap9741):1–9, 1 ("Sea levels are rising, with the highest rates in the tropics, where thousands of low-lying coral atoll islands are located. Most studies on the resilience of these islands to sea-level rise have projected that they will experience minimal inundation impacts until at least the

end of the 21st century. However, these have not taken into account the additional hazard of wave-driven overwash or its impact on freshwater availability. We project the impact of sea-level rise and wave-driven flooding on atoll infrastructure and freshwater availability under a variety of climate change scenarios. We show that, on the basis of current greenhouse gas emission rates, the nonlinear interactions between sea-level rise and wave dynamics over reefs will lead to the annual wave-driven overwash of most atoll islands by the mid-21st century. This annual flooding will result in the islands becoming uninhabitable because of frequent damage to infrastructure and the inability of their freshwater aquifers to recover between overwash events. This study provides critical information for understanding the timing and magnitude of climate change impacts on atoll islands that will result in significant, unavoidable geopolitical issues if it becomes necessary to abandon and relocate low-lying island states.").

[288] Storlazzi C. D., *et al.* (2018) *Most atolls will be uninhabitable by the mid-21st century because of sea-level rise exacerbating wave-driven flooding*, SCIENCE ADVANCES 4(eaap9741):1–9, 3 ("When the mean sea level is 1.0 m higher than that at present because of SLR, at least 50% of the island is projected to be flooded annually. This secondary tipping point—when most of Roi's land would be flooded annually—is projected to be reached in the 2055–2065 time frame for the RCP8.5+icesheet collapse climate scenario, the 2060–2070 time frame for the RCP8.5 scenario, and sometime after 2105 for the RCP4.5 scenario (Fig. 5). More than 90% of the island's surface is projected to be flooded annually when the mean sea level is 1.8 m higher than that at present because of SLR, which will likely be reached in the 2075–2085 time frame for the RCP8.5+icesheet collapse scenario and in the 2090–2100 time frame for the RCP8.5 scenario.").

[289] Storlazzi C. D., *et al.* (2018) *Most atolls will be uninhabitable by the mid-21st century because of sea-level rise exacerbating wave-driven flooding*, SCIENCE ADVANCES 4(eaap9741):1–9, 3 ("Thus, this "tipping point"—the time at which potable groundwater on Roi-Namur will be unavailable—is projected to be reached in the very near future, that is, within the life span of current residents and before 2030 for the RCP8.5+icesheet collapse climate scenario and within the 2030–2040 time frame for the RCP8.5 scenario and 2055–2065 for the RCP4.5 scenario. The 10-year ranges in these time frames take into account variability related to the El Nino–Southern Oscillation, which, in any given year, can cause regional sea level around Kwajalein to elevate or lower by 0.2 m for a few months (24).").

[290] Bouttes N., *et al.* (2013) *The Reversibility of Sea Level Rise*, J. CLIMATE 26:2502–2513, 2511 ("We have studied the future evolution of global mean sea level rise due to thermal expansion (i.e., not including contributions from ice sheets and glaciers) with an AOGCM under idealized CO_2 scenarios. Unlike surface temperature change, sea level change depends not only on the cumulative emission of CO_2 but also on the emission pathway. A greater rise in sea level results from earlier emissions than from later, for the same cumulative emission. Hence, targets to limit sea level rise would need to refer to rates of emissions as well as the total.").

[291] Bouttes N., *et al.* (2013) *The Reversibility of Sea Level Rise*, J. CLIMATE 26:2502–2513, 2502 ("Whereas surface temperature depends on cumulative CO_2 emissions, sea level rise due to thermal expansion depends on the time profile of emissions. Sea level rise is smaller for later emissions, implying that targets to limit sea level rise would need to refer to the rate of emissions, not only to the time integral.").

[292] Bittermann K., *et al.* (2017) *Global mean sea-level rise in a world agreed upon in Paris*, ENVTL. RESEARCH LETTERS 12(124010):1–9, 1 ("Although the 2015 Paris Agreement seeks to hold global average temperature to '*well below 2 ºC above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 ºC above pre-industrial levels*', projections of global mean sea-level (GMSL) rise commonly focus on scenarios in which there is a high probability that warming exceeds 1.5 ºC. Using a semi-empirical model, we project GMSL changes between now and 2150 CE under a suite of temperature scenarios that satisfy the Paris Agreement temperature targets. The projected magnitude and rate of GMSL rise varies among these low emissions scenarios. Stabilizing temperature at 1.5 ºC instead of 2 ºC above preindustrial reduces GMSL in 2150 CE by 17 cm (90% credible interval: 14–21 cm) and reduces peak rates of rise by 1.9 mm yr^{-1} (90% credible interval: 1.4–2.6 mm yr^{-1}). Delaying the year of peak temperature has little long-term influence on GMSL, but does reduce the maximum rate of rise. Stabilizing at 2 ºC in 2080 CE rather than 2030 CE reduces the peak rate by 2.7 mm yr^{-1} (90% credible interval: 2.0–4.0 mm yr^{-1}).").

[293] Bouttes N., *et al.* (2013) *The Reversibility of Sea Level Rise*, J. CLIMATE 26:2502–2513, 2505 ("Thus, because the thermosteric sea level is proportional to the time integral of the radiative forcing, the longer the forcing lasts, the bigger the change in thermosteric sea level rise (and oceanic temperature). The sea level change is the largest in the simulation where the largest fractional increase in the atmospheric burden of CO_2 occurs the earliest, which implies where CO_2 has been emitted the earliest. Because of a focus on impacts related to peak warming, it has been proposed that policy targets for avoiding dangerous climate change might be set in terms of cumulative CO_2 emission (Allen et al. 2009b). However, if we are concerned with mitigating sea level impacts, targets must be set on the rate of emission as well.").

[294] Bouttes N., *et al.* (2013) *The Reversibility of Sea Level Rise*, J. CLIMATE 26:2502–2513, 2511 ("Reducing the radiative forcing sufficiently would halt or reverse [sea-level rise], and a negative forcing would reverse it more quickly. Of course, reducing the forcing would require removal of CO_2 from the atmosphere or other geoengineering….").

[295] Arctic Monitoring and Assessment Programme (AMAP) (2017) SNOW, WATER, ICE, AND PERMAFROST IN THE ARCTIC: SUMMARY FOR POLICYMAKERS, 5 ("If increases in greenhouse gas concentrations continue at current rates, the melting of Arctic land-based ice would contribute an estimated 25 centimeters to sea-level rise between 2006 and 2100. Many of the smallest glaciers across the Arctic would disappear entirely by mid-century.").

[296] Schleussner C.-F., *et al.* (2016) *Differential Climate Impacts for Policy-Relevant Limits to Global Warming: the Case of 1.5ºC and 2ºC*, EARTH SYSTEM DYNAMICS 7:327–351, 342 ("For an illustrative 2ºC scenario, we project a median SLR of about 50 cm (36–65 cm, likely range) by 2100 and a rate of rise of 5.6 (4–7) mm yr^{-1} over the 2081–2100 period.").

[297] Schleussner C.-F., *et al.* (2016) *Differential Climate Impacts for Policy-Relevant Limits to Global Warming: the Case of 1.5ºC and 2ºC*, EARTH SYSTEM DYNAMICS 7:327–351, 342 ("For an illustrative 2ºC scenario, we project a median SLR of about 50 cm (36–65 cm, likely range) by 2100 and a rate of rise of 5.6 (4–7) mm yr^{-1} over the 2081–2100 period. Under our illustrative 1.5ºC scenario, projected SLR in 2100 is about 20% (or 10 cm) lower, compared to the 2ºC scenario…. The corresponding reduction in the expected rate of SLR over the 2081–2100 period is about 30%. More importantly, and in contrast to the projections for the 2ºC scenario, the rate for the 1.5ºC scenario is projected to decline between mid-century and the 2081–2100 period by about 0.5 mm yr^{-1}, which substantially reduces the multi-centennial SLR commitment (Schaeffer et al., 2012).").

[298] Schleussner C.-F., *et al.* (2016) *Differential Climate Impacts for Policy-Relevant Limits to Global Warming: the Case of 1.5ºC and 2ºC*, EARTH SYSTEM DYNAMICS 7:327–351, 342 ("Recent observational and modelling evidence indicates that a marine ice sheet instability in the West Antarctic may have already been triggered, which could lead to an additional SLR commitment of about 1 m on a multi-centennial timescale. …Mengel and Levermann (2014) report a potential marine ice-sheet instability for the Wilkens Basin in West Antarctica containing 3–4 m of global SLR. The dynamics of these coupled cryosphere-oceanic systems remain a topic of intense research.").

[299] Pattyn F., *et al.* (2018) *The Greenland and Antarctic ice sheets under 1.5 ºC global warming*, NATURE CLIMATE CHANGE 8:1053–1061, 1053 ("Even if anthropogenic warming were constrained to less than 2 °C above pre-industrial, the Greenland and Antarctic ice sheets will continue to lose mass this century, with rates similar to those observed over the past decade. However, nonlinear responses cannot be excluded, which may lead to larger rates of mass loss. Furthermore, large uncertainties in future projections still remain, pertaining to knowledge gaps in atmospheric (Greenland) and oceanic (Antarctica) forcing. On millennial timescales, both ice sheets have tipping points at or slightly above the 1.5–2.0 °C threshold; for Greenland, this may lead to irreversible mass loss due to the surface mass balance–elevation feedback, whereas for Antarctica, this could result in a collapse of major drainage basins due to ice-shelf weakening.").

[300] Pattyn F., *et al.* (2018) *The Greenland and Antarctic ice sheets under 1.5 ºC global warming*, NATURE CLIMATE CHANGE 8:1053–1061, 1055 ("For the long-term evolution of the ice sheets, on multicentennial to multimillennial timescales, feedbacks with the atmosphere and ocean increase in importance. When subjected to perturbed climatic forcing over this timescale, the ice sheets manifest large changes in their volume and distribution. These changes typically occur with a significant lag in response to the forcing applied, which leads to the concept of climate commitment: changes that will occur in the long-term future are committed to at a much earlier stage. Because of the long residence time of CO_2 in the atmosphere, climate change in coming decades will most probably last long enough to dictate ice-sheet evolution over centuries and millennia. Furthermore, the ice sheets are subject to threshold behaviour in their stability, as a change in boundary conditions such as climate forcing can cause the current ice-sheet configuration to become unstable. Crossing this tipping point leads the system to equilibrate to a qualitatively different state (by melting completely, for example). The existence of a tipping point implies that ice-sheet changes are potentially irreversible—returning to a pre-industrial climate may not stabilize the ice sheet once the tipping point has been crossed. A key concept here is the timeframe of reversal, because many ice-sheet changes may only be reversible over a full glacial–interglacial cycle with natural rates of changes in climatic variables. For both Greenland and Antarctica tipping points are known to exist for warming levels that could be reached before the end of this century. The unprecedented rate of increase in GHGs over the Anthropocene leaves the question of irreversible crossing of tipping points unresolved. For example, it is possible that the expected future increase in GHGs will prevent or delay the next ice-sheet inception.").

[301] Dutton A., *et al.* (2015) *Sea-level rise due to polar ice-sheet mass loss during past warm periods*, SCIENCE 349(6244):aaa4019-1–aaa4019-9, aaa4019-7 ("Improving our understanding of individual polar ice-sheet

contributions to GMSL is a key challenge. An important uncertainty for future projections of the GrIS is the threshold temperature beyond which it undergoes irreversible retreat, with current estimates ranging from 1º to 4ºC above preindustrial temperatures. Improved estimates of GrIS loss for a given local or global temperature increase during past warm periods will thus provide a critical constraint on this threshold. For the AIS, the key challenge involves determining which marine-based sectors are most vulnerable to collapse and identifying the forcing (atmospheric or oceanic) that would trigger such events. Paleoconstraints on past ice-sheet mass loss and forcings will be of particular value for validation of coupled ice sheet-climate models.").

[302] Bassis J. N., *et al.* (2017) *Heinrich events triggered by ocean forcing and modulated by isostatic adjustment*, NATURE 542:332–334, 332 ("Figure 1 | Stages of the proposed Heinrich event mechanism. With the ice sheet in its most advanced state, the terminus is grounded 300 m beneath sea level (a). An ocean-warming event triggers retreat (b), which is further amplified by enhanced calving as the ice sheet retreats into deeper water (c). After the collapse, the ice sheet is in its most retreated position (d), with the elevated sill cutting off contact with the warm subsurface waters. Isostatic adjustment uplifts the bed allowing the ice sheet to advance again. Insets show a close-up around the sill.").

[303] Bassis J. N., *et al.* (2017) *Heinrich events triggered by ocean forcing and modulated by isostatic adjustment*, NATURE 542:332–334, 333 ("Our simulated Heinrich events show a pattern of rapid retreat followed by slow advance (Figs 1 and 2…). When the ice is at its full extent (Fig. 1a), the deepest portion of the bed is depressed more than 1 km beneath sea level, comparable to modern marine-based ice sheets. …A small warming in the subsurface ocean triggers rapid retreat of the ice sheet into the over-deepening bed (Fig. 1b, c). Retreat continues until isostatic adjustment allows the bed (and sill) to rise, isolating the terminus from ocean forcing. At this point, retreat ceases and, with the ice sheet at its minimum extent, bed uplift facilitates regrowth on a slower timescale than collapse (Fig. 1d).").

[304] Bassis J. N., *et al.* (2017) *Heinrich events triggered by ocean forcing and modulated by isostatic adjustment*, NATURE 542:332–334, 332 ("During the last glacial period, the Laurentide Ice Sheet sporadically discharged huge numbers of icebergs through the Hudson Strait into the North Atlantic Ocean, leaving behind distinct layers of ice-rafted debris in the ocean sediments. Perplexingly, these massive discharge events—Heinrich events—occurred during the cold portion of millennial-scale climate oscillations called Dansgaard–Oeschger cycles. This is in contrast to the expectation that ice sheets expand in colder climates and shrink in warmer climates. Here we use an ice sheet model to show that the magnitude and timing of Heinrich events can be explained by the same processes that drive the retreat of modern marine-terminating glaciers. In our model, subsurface ocean warming associated with variations in the overturning circulation increases underwater melt along the calving face, triggering rapid margin retreat and increased iceberg discharge. On millennial timescales, isostatic adjustment causes the bed to uplift, isolating the terminus from subsurface warming and allowing the ice sheet to advance again until, at its most advanced position, it is poised for another Heinrich event. This mechanism not only explains the timing and magnitude of observed Heinrich events, but also suggests that ice sheets in contact with warming oceans may be vulnerable to catastrophic collapse even with little atmospheric warming.").

[305] DeConto R. M. & Pollard D. (2016) *Contribution of Antarctica to past and future sea-level rise*, NATURE 531:591–597, 591 ("Reconstructions of the global mean sea level (GMSL) during past warm climate intervals including the Pliocene (about three million years ago) and late Pleistocene interglacials imply that the Antarctic ice sheet has considerable sensitivity. Pliocene atmospheric CO_2 concentrations were comparable to today's (~400 parts per million by volume, p.p.m.v.), but some sea-level reconstructions are 10–30 m higher.").

[306] DeConto R. M. & Pollard D. (2016) *Contribution of Antarctica to past and future sea-level rise*, NATURE 531:591–597, 591 ("During the more recent Last Interglacial (LIG, 130,000 to 115,000 years ago), GMSL was 6–9.3 m higher than it is today, at a time when atmospheric CO_2 concentrations were below 280 p.p.m.v. and global mean temperatures were only about 0–2ºC warmer.").

[307] DeConto R. M. & Pollard D. (2016) *Contribution of Antarctica to past and future sea-level rise*, NATURE 531:591–597, 591 ("This requires a substantial sea-level contribution from Antarctica of 3.6–7.4 m in addition to an estimated 1.5–2 m from Greenland and around 0.4 m from ocean steric effects.").

[308] Robinson A., *et al.* (2012) *Multistability and critical thresholds of the Greenland ice sheet*, NATURE CLIMATE CHANGE 2:429–432, 429 ("Recent studies have focused on the short-term contribution of the Greenland ice sheet to sea-level rise, yet little is known about its long-term stability. The present best estimate of the threshold in global temperature rise leading to complete melting of the ice sheet is 3.1 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.").

[309] Pattyn F., *et al.* (2018) *The Greenland and Antarctic ice sheets under 1.5 ºC global warming*, NATURE CLIMATE CHANGE 8:1053–1061, 1053 ("Greenland has warmed by ~5 °C in winter and ~2 °C in summer since the mid-1990s, which is more than double the global mean warming rate in that period. The GrIS has also been losing mass at an increasing rate since the 1990s with 0.65–0.73 mm yr^{-1} of mean SLR equivalent (s.l.e.) for 2012–2016. Since 2000, both SMB decrease and ice discharge increase contributed to mass loss, but the relative contribution of SMB decrease to the total mass loss went up from 42% to 68% between 2000 and 2012. The current observed SMB decrease is mainly driven by increased melt and subsequent runoff and is in part attributed to anthropogenic global warming and concurrent Arctic amplification (exacerbated Arctic warming due to regional feedbacks of global warming), but also to recent atmospheric circulation changes in summer observed since the 2000s. The occurrence of a negative North Atlantic Oscillation (NAO) and a concurrent positive phase of the East Atlantic Pattern since 2000 can be interpreted as a weakening and southward displacement of the jet stream, allowing for anomalous high pressure and enhanced atmospheric blocking over the GrIS. These circulation changes in summer have favoured the advection of warm southerly air masses and increased incoming solar radiation, leading to more melt, which is further enhanced by the melt–albedo feedback.").

[310] Hofer S., *et al.* (2017) *Decreasing cloud cover drives the recent mass loss on the Greenland Ice Sheet*, SCIENCE ADVANCES 3(e1700584):1–8, 1 ("Until the mid-1990s, losses from surface meltwater runoff and ice discharge into the ocean (D) were roughly balanced by snow accumulation (1, 2). However, since then, mass loss has accelerated (3) as the surface mass balance (SMB) has declined and D has increased (1), with a possible link between meltwater production and ice dynamics (4, 5). As a consequence, the GrIS has become the dominant source of barystatic sea level rise, with an average (1991–2015) contribution of 0.47 ± 0.23 mm/year [equivalent to 171 gigatons (Gt) of ice] (2).").

[311] Tedesco M., *et al.* (2016) *Greenland Ice Sheet*, *in* ARCTIC REPORT CARD ("The Greenland ice sheet plays a crucial role globally and locally, impacting the surface energy budget and climate and weather and contributing to current and future sea level rise. Estimates of the spatial extent of surface melt across the Greenland ice sheet (GrIS), over the period 1979 to 2016, are derived from brightness temperatures measured by the Special Sensor Microwave Imager/Sounder passive microwave radiometer (e.g., Mote 2007, Tedesco et al. 2013). Though 2016 was not a record-breaking year in terms of melt extent and duration, it extends the overall increasing melting trend. The updated trend for melt extent over the period 1979–2016 over the whole Greenland ice sheet is +15,824 km^2/yr.").

[312] Bevis M., *et al.* (2019) *Accelerating changes in ice mass within Greenland, and the ice sheet's sensitivity to atmospheric forcing*, PROC. NAT'L. ACAD. SCI. 116(6):1934–1939, 1934 ("From early 2003 to mid-2013, the total mass of ice in Greenland declined at a progressively increasing rate. In mid-2013, an abrupt reversal occurred, and very little net ice loss occurred in the next 12–18 months. Gravity Recovery and Climate Experiment (GRACE) and global positioning system (GPS) observations reveal that the spatial patterns of the sustained acceleration and the abrupt deceleration in mass loss are similar. The strongest accelerations tracked the phase of the North Atlantic Oscillation (NAO). The negative phase of the NAO enhances summertime warming and insolation while reducing snowfall, especially in west Greenland, driving surface mass balance (SMB) more negative, as illustrated using the regional climate model MAR. The spatial pattern of accelerating mass changes reflects the geography of NAO-driven shifts in atmospheric forcing and the ice sheet's sensitivity to that forcing. We infer that southwest Greenland will become a major future contributor to sea level rise.").

[313] Lenton T. M. (2012) *Arctic Climate Tipping Points*, AMBIO, 41:10–22, 15 ("The GIS is currently losing mass at a rate that has been accelerating (Rignot et al. 2007). In summer 2007, there was an unprecedented increase in surface melt, mostly south of 70°N and also up the west side of Greenland, due to an up to 50-day longer melt season than average with an earlier start (Mote 2007). This is part of a longer-term trend of increasing melt extent since the 1970s. Recent observations show that seasonal surface melt has led to accelerated glacier flow (Joughin et al. 2008; van de Wal et al. 2008). The surface mass balance of the GIS is still positive (there is more incoming snowfall than melt at the surface, on an annual average), but the overall mass balance of the GIS is negative due to an increased loss flux from calving of glaciers that outweighs the positive surface mass balance. The margins of the GIS are

thinning at all latitudes (Pritchard et al. 2009), and the rapid retreat of calving glaciers terminating in the ocean, most notably Jakobshavn Isbrae, is probably linked to warming ocean waters (Holland et al. 2008).").

[314] Arctic Monitoring and Assessment Programme (AMAP) (2017) SNOW, WATER, ICE, AND PERMAFROST IN THE ARCTIC: SUMMARY FOR POLICYMAKERS, 4 ("Since at least 1972 the Arctic has been the dominant source of global sea-level rise. Seventy percent of the Arctic's contribution to sea-level rise comes from Greenland, which on average lost 375 gigatons of ice per year—equivalent to a block of ice measuring 7.5 kilometers or 4.6 miles on all sides—from 2011 to 2014. This is close to twice the rate over the period 2003–2008.").

[315] Tedesco M., *et al.* (2017) *Greenland Ice Sheet*, *in* ARCTIC REPORT CARD 2017 ("Reflecting surface air temperature patterns over the Greenland ice sheet, the April 2016–April 2017 season was characterized by relatively low summer (June, July, August) melt extent and ablation along the margins of the ice sheet. Correspondingly, the surface albedo, averaged over the entire ice sheet, was relatively high. The net ice mass loss over the year was near average."); *see also* News Release, National Oceanic and Atmospheric Administration (NOAA), *Arctic saw 2nd warmest year, smallest winter sea ice coverage on record in 2017* (12 December 2017) ("Less melt on Greenland Ice Sheet. Melting began early on the Greenland Ice Sheet in 2017, but slowed during a cooler summer, resulting in below-average melting when compared to the previous nine years. Overall, the Greenland Ice Sheet, a major contributor to sea level rise, continued to lose mass this past year, as it has since 2002 when measurements began.").

[316] Tedesco M., *et al.* (2018) *Greenland Ice Sheet*, *in* ARCTIC REPORT CARD 2018, 17 ("Estimates of the spatial extent of melt across the Greenland ice sheet (GrIS) were unexceptional for most of summer melt season of 2018. Observations derived from brightness temperatures (a measure of a body's natural radiance) measured by the Special Sensor Microwave Imager/Sounder (SSMIS) passive microwave radiometer (e.g., Mote, 2007; Tedesco et al., 2013), indicated that melt extent exceeded (i.e., conditions were warmer) by one standard deviation in early June and again briefly in late July and early August (Fig. 1a). During the middle of the season, from mid-June to mid-July, the spatial extent of melting remained largely within the interquartile range of the 1981-2010 mean. The spatial extent of melt for the period of June, July, and August (JJA) 2018 was above average on only 26% of the summer days. During the same period of 2017, another low melt year, only 16% of days were above the average.").

[317] Tedesco M., *et al.* (2018) *Greenland Ice Sheet*, *in* ARCTIC REPORT CARD 2018, 20 ("The summer (JJA) 2018 albedo averaged over the whole Greenland ice sheet was 81.7% (Fig. 3a), as estimated from the Moderate Resolution Imaging Spectroradiometer (MODIS; after Box et al., 2017). The 2018 summer albedo is tied with 2000 for the highest value recorded during the 19-year MODIS period of observation (i.e., 2000-18). The months of June and July had record high albedo. The high albedo anomalies along most of the coastline (Fig. 3b) are consistent with reduced melting in summer 2018, which resulted in late surviving snow over the darkest bare ice areas. The minimum average summer albedo was recorded in 2012 (76.8%), the year of record maximum melt extent. Albedos have been relatively high since 2012. Consistently with MODIS estimates, measurements at the S9 K-transect station show higher than usual albedo values (Fig. 2c), which are also strongly correlated with the surface mass balance values measured at the same location. In summary, summer 2018 albedo, averaged over the whole ice sheet, was relatively high for the 2000–18 period, matching the value of the record high set in 2000.").

[318] Tedesco M., *et al.* (2016) *Arctic cut-off high drives the poleward shift of a new Greenland melting record*, NATURE COMMUNICATIONS 7(11723):1–6, 4 ("Our work presented here demonstrates a strong need to identify the mechanisms that create and maintain strong cutoff highs. The new atmospheric records, and the trends of mean zonal winds and wave amplitude of the jet stream are consistent with the suggested effects of Arctic amplification. Recent studies provide theoretical arguments that slowing zonal winds might be associated with larger planetary wave amplitudes and that Arctic amplification and/or sea-ice loss do intensify existing ridges, thereby contributing to their persistence.").

[319] Tedesco M., *et al.* (2016) *Arctic cut-off high drives the poleward shift of a new Greenland melting record*, NATURE COMMUNICATIONS 7(11723):1–6, 1 ("Here, using reanalysis data and the outputs of a regional climate model, we show that the persistence of an exceptional atmospheric ridge, centred over the Arctic Ocean, was responsible for a poleward shift of runoff, albedo and surface temperature records over the Greenland during the summer of 2015. New records of monthly mean zonal winds at 500hPa and of the maximum latitude of ridge peaks of the 5,700±50m isohypse over the Arctic were associated with the formation and persistency of a cutoff high. The unprecedented (1948–2015) and sustained atmospheric conditions promoted enhanced runoff, increased the surface temperatures and decreased the albedo in northern Greenland, while inhibiting melting in the south, where new melting records were set over the past decade.").

[320] Hofer S., *et al.* (2017) *Decreasing cloud cover drives the recent mass loss on the Greenland Ice Sheet*, SCIENCE ADVANCES 3(e1700584):1–8, 5 ("Climate warming is instead altering large-scale circulation patterns (Fig. 4 and figs. S1 and S2) (13, 20, 22, 23), which then causes an even larger response in the local energy budget of the GrIS

by enhancing not only the atmospheric temperature but also the solar insolation. Furthermore, our results indicate that the recent decline in surface reflectivity is partly caused by SWD anomalies by enhancing the melt-albedo feedback and the spectrum of radiation reaching the surface (fig. S4) (8, 18).”).

[321] Hofer S., *et al.* (2017) *Decreasing cloud cover drives the recent mass loss on the Greenland Ice Sheet*, SCIENCE ADVANCES 3(e1700584):1–8, 1 (“The decrease in cloud cover that occurred after 2002 is relatively large, with substantial parts of southern Greenland experiencing a reduction of more than 10%. These cloudiness changes are a direct response to the circulation changes observed since the end of the 1990s (13). As shown in Fig. 1 (A and B, bottom), these circulation changes favor more anticyclonic conditions (warm and dry) over the south of Greenland except in the northeast where they favor southward fluxes (wet and cold), explaining the cloudiness increase in this area. During 1982–2009, the increases in geopotential height of the 500-hPa pressure level (Z500) promoted more anticyclonic conditions over most of Greenland, whereas during 2002–2015, the Z500 increases are limited to the west coast.”).

[322] Hofer S., *et al.* (2017) *Decreasing cloud cover drives the recent mass loss on the Greenland Ice Sheet*, SCIENCE ADVANCES 3(e1700584):1–8, 4 (“Therefore, the exceptional melt of the GrIS since the mid-1990s has appeared to be a result of increases in both of the “external” drivers of the surface energy balance, LWD and SWD. Whereas previous studies have focused on the role of rising temperatures as the main cause of the current melt increase and albedo decline over the GrIS [for example, (15, 16)], our results strongly indicate that it is rather a combination of increased SWD due to reduced cloud cover in summer combined with an increase in LWD due to higher free-atmosphere temperatures causing melt and surface darkening. Therefore, the decrease in surface albedo due to the melt-albedo feedback (8), which increases surface melt by increasing the ratio of absorbed solar radiation, has also been partly driven by a recent decrease in summer cloud cover enhancing the melt-albedo feedback (see also fig. S4) and not only by temperature anomalies.”).

[323] Noël B., *et al.* (2017) *A tipping point in refreezing accelerates mass loss of Greenland’s glaciers and ice caps*, NATURE COMMUNICATIONS 8(14730):1–8, 1 (“Melting of the Greenland ice sheet (GrIS) and its peripheral glaciers and ice caps (GICs) contributes about 43% to contemporary sea level rise. While patterns of GrIS mass loss are well studied, the spatial and temporal evolution of GICs mass loss and the acting processes have remained unclear. Here we use a novel, 1 km surface mass balance product, evaluated against in situ and remote sensing data, to identify 1997 (±5 years) as a tipping point for GICs mass balance. That year marks the onset of a rapid deterioration in the capacity of the GICs firn to refreeze meltwater. Consequently, GICs runoff increases 65% faster than meltwater production, tripling the post-1997 mass loss to 36±16Gt^{-1}, or ~14% of the Greenland total. In sharp contrast, the extensive inland firn of the GrIS retains most of its refreezing capacity for now, buffering 22% of the increased meltwater production. This underlines the very different response of the GICs and GrIS to atmospheric warming.”).

[324] Machguth H., *et al.* (2016) *Greenland meltwater storage in firn limited by near-surface ice formation*, NATURE CLIMATE CHANGE 6:390–393, 390 (“Approximately half of Greenland’s current annual mass loss is attributed to runoff from surface melt. At higher elevations, however, melt does not necessarily equal runoff, because meltwater can refreeze in the porous near-surface snow and firn. Two recent studies suggest that all or most of Greenland’s firn pore space is available for meltwater storage, making the firn an important buffer against contribution to sea level rise for decades to come. Here, we employ *in situ* observations and historical legacy data to demonstrate that surface runoff begins to dominate over meltwater storage well before firn pore space has been completely filled. Our observations frame the recent exceptional melt summers in 2010 and 2012, revealing significant changes in firn structure at different elevations caused by successive intensive melt events. In the upper regions (more than ~1,900m above sea level), firn has undergone substantial densification, while at lower elevations, where melt is most abundant, porous firn has lost most of its capability to retain meltwater. Here, the formation of near-surface ice layers renders deep pore space difficult to access, forcing meltwater to enter an efficient surface discharge system and intensifying ice sheet mass loss earlier than previously suggested.”).

[325] Ahlstrøm A. P., *et al.* (2017) *Abrupt shift in the observed runoff from the southwestern Greenland ice sheet*, SCIENCE ADVANCES 3(e1701169):1–7, 1 (“We present for the first time a 40-year (1975–2014) time series of observed meltwater discharge from a >6500-km^2 catchment of the southwestern Greenland ice sheet. We find that an abrupt 80% increase in runoff occurring between the 1976–2002 and 2003–2014 periods is due to a shift in atmospheric circulation, with meridional exchange events occurring more frequently over Greenland, establishing the first observation-based connection between ice sheet runoff and climate change.”).

[326] Fürst J. J., *et al.* (2015) *Ice-dynamic projections of the Greenland ice sheet in response to atmospheric and oceanic warming*, CRYOSPHERE 9:1039–1062, 1039 (“During the last decade (2000–2010), both increased melt-water runoff and enhanced ice discharge from calving glaciers have contributed 0.6 ± 0.1 mm yr^{-1} to global sea-level rise, with a relative contribution of 60 and 40 % respectively.”).

[327] Fürst J. J., *et al.* (2015) *Ice-dynamic projections of the Greenland ice sheet in response to atmospheric and oceanic warming*, CRYOSPHERE 9:1039–1062, 1039 ("For a suite of 10 atmosphere and ocean general circulation models and four representative concentration pathway scenarios, the projected sea-level rise between 2000 and 2100 lies in the range of +1.4 to +16.6 cm. For two low emission scenarios, the projections are conducted up to 2300. Ice loss rates are found to abate for the most favourable scenario where the warming peaks in this century, allowing the ice sheet to maintain a geometry close to the present-day state. For the other moderate scenario, loss rates remain at a constant level over 300 years. In any scenario, volume loss is predominantly caused by increased surface melting as the contribution from enhanced ice discharge decreases over time and is self-limited by thinning and retreat of the marine margin, reducing the ice–ocean contact area.").

[328] Fürst J. J., *et al.* (2015) *Ice-dynamic projections of the Greenland ice sheet in response to atmospheric and oceanic warming*, CRYOSPHERE 9:1039–1062, 1039 ("In the 30-year period prior to 1990, the ice sheet has been in a virtual balance with the prevailing climate but has since been losing mass at an increasing rate (Rignot et al., 2011; Zwally et al., 2011; Shepherd et al., 2012; Sasgen et al., 2012). Almost half of this recent mass loss is attributed to increased ice discharge at the marine margins (van den Broeke et al., 2009; Shepherd et al., 2012; Sasgen et al., 2012; Vaughan et al., 2013), with a tendency towards relatively more surface melting since 2005 (Csatho et al., 2014; Enderlin et al., 2014). During the period 1972 to 1995, glacier terminus positions and ice flow were rather stable around Greenland (Moon and Joughin, 2008; Howat and Eddy, 2011; Bevan et al., 2012).").

[329] Trusel L. D., *et al.* (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.").

[330] Trusel L. D., *et al.* (2018) *Nonlinear rise in Greenland runoff in response to post-industrial Arctic warming*, NATURE 564:104–108, 106 ("Our ice-core results provide further context and reveal that these 2012 melt rates are exceptional highs for at least the past 350 years. If an air-temperature reconstruction from the nearby Canadian Arctic is regionally representative, GrIS melt and runoff experienced in the last decade is likely also to be unprecedented over the last 6,800–7,800 years. The nonlinear melt–temperature sensitivity also helps explain why episodes of mid-twentieth-century warmth resulted in less intense and less sustained melting compared to the last two decades, despite being only marginally cooler (Fig. 2). Additional factors, such as recent sea-ice losses, as well as regional and teleconnected general circulation changes, may also play a part in amplifying the melt response. Moreover, this melt–temperature nonlinearity indicates that only limited additional warming will greatly enhance the area of the ice sheet subject to meltwater runoff.").

[331] Fürst J. J., *et al.* (2015) *Ice-dynamic projections of the Greenland ice sheet in response to atmospheric and oceanic warming*, CRYOSPHERE 9:1039–1062, s1053 ("Our results have implications for attempts to estimate the role of ice discharge on the future mass loss of the Greenland ice sheet. Observed rates of change over the last decade cannot simply be extrapolated over the 21st century on account of a different balance of processes causing mass loss over time. Extrapolating recently inferred mass trends (Pfeffer et al., 2008) or even changes therein to a century timescale (Rignot et al., 2011) or linking observed Greenland sea-level trends to temperature change (Rahmstorf, 2007) implies continued glacier acceleration and a multifold increase of the ice discharge that is not found attainable in numerical ice-sheet models. Ice discharge at calving fronts is self-limited by ice dynamics, supporting the view that centennial mass changes are dominantly driven by SMB changes, and thus by changes in surface climate conditions.").

[332] Trusel L. D., *et al.* (2018) *Nonlinear rise in Greenland runoff in response to post-industrial Arctic warming*, NATURE 564:104–108, 106 ("Our reconstruction quantifies the exceptional magnitude of present- day melt and runoff relative to the last several centuries. Their rapid intensification over the last two decades also illustrates a clear non- linear melt–temperature relationship (Fig. 4c; Methods). Similar late-twentieth-century melt acceleration was found using records from an Antarctic Peninsula ice core, and attributed to a nonlinear response of melting to climate warming more broadly across Antarctica, owing largely to the melt–albedo positive feedback. At all of our

core sites, 2012 melt was more intense than any other year according to two distinct reanalysis-forced regional climate models that extend back to 1958 and 1979 (Fig. 4c).").

333 Parizek B. R., *et al.* (2019) *Ice-cliff failure via retrogressive slumping*, GEOLOGY, Online Publication, 1–4, 1 ("Retrogressive slumping could accelerate sea-level rise if ice-sheet retreat generates ice cliffs much taller than observed today. The tallest ice cliffs, which extend roughly 100 m above sea level, calve only after ice-flow processes thin the ice to near flotation. Above some ice-cliff height limit, the stress state in ice will satisfy the material-failure criterion, resulting in faster brittle failure. New terrestrial radar data from Helheim Glacier, Greenland, suggest that taller subaerial cliffs are prone to failure by slumping, unloading submarine ice to allow buoyancy-driven full-thickness calving. Full-Stokes diagnostic modeling shows that the threshold cliff height for slumping is likely slightly above 100 m in many cases, and roughly twice that (145–285 m) in mechanically competent ice under well-drained or low-melt conditions.").

334 Tedesco M., *et al.* (2016) *The darkening of the Greenland ice sheet: trends, drivers, and projections (1981–2100)*, THE CRYOSPHERE 10:477–496, 478 ("The presence of LAI such as soot (black carbon, BC), dust, organic matter, algae, and other biological material in snow or ice also reduces the albedo, mostly in the visible and ultraviolet regions (Warren, 1982). Such impurities are deposited through dry and wet deposition, and their mixing ratios are enhanced through snow water loss in sublimation and melting (Conway et al., 1996; Flanner et al., 2007; Doherty et al., 2013). Besides grain growth and LAI, another cause of albedo reduction over the GrIS is the exposure of bare ice: once layers of snow or firn are removed through ablation, the exposure of the underlying bare ice will further reduce surface albedo, as does the presence of melt pools on the ice surface (e.g. Tedesco et al., 2011).").

335 Lutz S., *et al.* (2016) *The biogeography of red snow microbiomes and their role in melting arctic glaciers*, NATURE COMMUNICATIONS 7(11968):1–9, 2 ("We have recently shown that snow algae are critical players in glacial surface habitats and the dominating biomass immediately after the onset of melting. Snow algae are prolific primary colonizers and producers that can form extensive blooms in spring and summer. Such snow algal blooms can substantially darken the surface of glaciers because of their red pigmentation (secondary carotenoids), which the algae produce as a protection mechanism (for example, from high levels of irradiation). We have shown that this phenomenon, known as 'red snow', can reduce the surface albedo locally by up to 20%, which in turn further increases melting rates of snow.").

336 Lutz S., *et al.* (2016) *The biogeography of red snow microbiomes and their role in melting arctic glaciers*, NATURE COMMUNICATIONS 7(11968):1–9, 5 ("The above documented high algal biomass primarily made up of highly red pigmented algae, will invariably affect the amount of light that is reflected from the surface of snow fields. Our albedo measurements…showed a clear decrease in surface albedo in comparison to algal-free snow sites (0.90±0.05…). The measured decrease where red pigmented algae were present was similar in all sites, independent of the local environment with albedo values reaching between ~0.50 and 0.75…. In addition, we found a significant (P ¼ 0.008) negative correlation between algal biomass and surface albedo…, which clearly supports our assertion of the crucial role of red pigmented snow algae in decreasing surface albedo and increasing melting. …Moreover, with further melting dirty ice and cryoconite holes will be exposed earlier and their albedo values can drop by an additional ~20% to 0.34±0.15. This will likely culminate in even higher melt rates….").

337 Lutz S., *et al.* (2016) *The biogeography of red snow microbiomes and their role in melting arctic glaciers*, NATURE COMMUNICATIONS 7(11968):1–9, 5–6 ("A quantitative value for the area of Arctic glaciers and the Greenland Ice Sheet covered by snow algae during a melt season is still lacking. However, as we infer from our data, melting is one major driver for snow algal growth. Extreme melt events like that in 2012, when 97% of the entire Greenland Ice Sheet was affected by surface melting, are likely to re-occur with increasing frequency in the near future as a consequence of global warming.").

338 Tedesco M., *et al.* (2016) *The darkening of the Greenland ice sheet: trends, drivers, and projections (1981–2100)*, THE CRYOSPHERE 10:477–496, 492 ("The drivers we identified to be responsible for the observed darkening are related to endogenous processes rather than exogenous ones and are strongly driven by melting. Because melting is projected to increase over the next decades, it is crucial to assess our capability of studying, quantifying, and projecting these processes as they will inevitably impact, and be impacted by, future scenarios.").

339 Stibal M., *et al.* (2017) *Algae Drive Enhanced Darkening of Bare Ice on the Greenland Ice Sheet*, GEOPHYSICAL RESEARCH LETTERS 44:11,463–11,471, 11,463 ("Surface ablation of the Greenland ice sheet is amplified by surface darkening caused by light-absorbing impurities such as mineral dust, black carbon, and pigmented microbial cells. We present the first quantitative assessment of the microbial contribution to the ice sheet surface darkening, based on field measurements of surface reflectance and concentrations of light-absorbing impurities, including pigmented algae, during the 2014 melt season in the southwestern part of the ice sheet. The impact of algae on bare ice

darkening in the study area was greater than that of nonalgal impurities and yielded a net albedo reduction of 0.038 ± 0.0035 for each algal population doubling. We argue that algal growth is a crucial control of bare ice darkening, and incorporating the algal darkening effect will improve mass balance and sea level projections of the Greenland ice sheet and ice masses elsewhere.").

[340] Tedesco M., *et al.* (2016) *The darkening of the Greenland ice sheet: trends, drivers, and projections (1981–2100)*, THE CRYOSPHERE 10:477–496, 493 ("The regions of Greenland that are darkening the most rapidly are within the ablation zone. Here, there is no direct evidence that the rate of atmospheric deposition of LAI has been increasing. In view of the cumulative effect of snowmelt leaving impurities at the surface, the intra-seasonal variation of deposition may not be as important as the exposure of LAI by melting. Changes in the abundances of light-absorbing algae and other organic material with warmer temperatures may also be contributing to declining albedo, particularly for the ice, but this is an essentially unstudied source of darkening.").

[341] Tedesco M., *et al.* (2016) *The darkening of the Greenland ice sheet: trends, drivers, and projections (1981–2100)*, THE CRYOSPHERE 10:477–496, 490 ("Our results show a darkening of the GrIS 1996–2012, and indicate that this darkening is associated with increased surface snow grain size, an expansion in the area and persistence of bare ice, and by an increase in surface snow light-absorbing impurity (LAI) concentrations. We find no evidence for general increases in the deposition of LAI across the GrIS, so we associate the higher surface snow impurity concentrations predominantly with the appearance of underlying dirty ice and the consolidation of LAI in surface snow resulting from snow melt.").

[342] Stephenson S. R., *et al.* (2018) *Climatic responses to future trans-Arctic shipping*, GEOPHYSICAL RESEARCH LETTERS 45:9898–9908, 9898 ("Because warming favors increased shipping traffic, previous studies have focused on the potential for ship emissions of black carbon (BC) and other particulates to enhance warming by lowering the otherwise high albedo of ice and snow (Browse et al., 2013; Corbett et al., 2010; Ødemark et al., 2012; Sand et al., 2016). The source of emissions is an important factor in determining the magnitude of this feedback and their ultimate climatic impact. Unlike BC transported to the Arctic from these midlatitude sources in Russia and Asia (Winiger et al., 2017; Wobus et al., 2016), strong surface inversions in the Arctic boundary layer make it more likely that BC emitted in the Arctic will be deposited on ice and snow, thereby maximizing its impact on surface temperature.").

[343] Pattyn F., *et al.* (2018) *The Greenland and Antarctic ice sheets under 1.5 ºC global warming*, NATURE CLIMATE CHANGE 8:1053–1061, 1055 ("On longer timescales (Box 2), a tipping point (when the ice sheet enters a state of irreversible mass loss and complete melting is initiated) exists as part of the coupled ice sheet–atmospheric system. This consists of two interrelated feedback mechanisms: the SMB–elevation feedback, as described above, and the melt–albedo feedback. The latter acts on the surface energy balance, by allowing more absorption of solar radiation from a melting and darkening snow surface, or removal of all snow leading to a darker ice surface. This feedback may be enhanced by ice-based biological processes, such as the growth of algae. Thus, the activation of these feedbacks can lead to self-sustained melting of the entire ice sheet, even if the anomalous climatic forcing is removed.").

[344] Pattyn F., *et al.* (2018) *The Greenland and Antarctic ice sheets under 1.5 ºC global warming*, NATURE CLIMATE CHANGE 8:1053–1061, 1054 ("A decrease in SMB lowers the ice-sheet surface, which in turn lowers SMB because at lower elevations, near-surface air temperature is generally higher. Additional SMB changes due to the SMB–surface elevation feedback are small for limited warming: in a coupled SMB–ice dynamical simulation, the feedback contributes 11% to the GrIS runoff rate in an RCP2.6 scenario, or ~3 mm of additional SLR by 2100.").

[345] Oltmanns M., *et al.* (2019) *Increased Greenland melt triggered by large-scale, year-round cyclonic moisture intrusions*, CRYOSPHERE 13:815–825, 824 ("A decomposition of the synoptic atmospheric variability over Greenland suggested that the identified, melt-triggering weather pattern has accounted for ~40 % of the total precipitation. Yet, the observed increases in the occurrence and areal extent of the initiated melting have led to a more frequent replacement of snow by rain and a northward and upslope shift of the boundary between rain/melting and snowfall, hence changing the balance between Greenland's mass gain and mass loss within a single weather event. Using a regional climate model, we estimated that the melting associated with melt events more than doubled in summer and more than tripled in winter, amounting to ~28 % of the overall melt. Thus, we conclude that, despite the involved mass gain, year-round precipitation events are contributing to the ice sheet's decline.").

[346] Oltmanns M., *et al.* (2019) *Increased Greenland melt triggered by large-scale, year-round cyclonic moisture intrusions*, CRYOSPHERE 13:815–825, 819 ("All investigated stations record an increased absorption of longwave radiation (Fig. 5c), suggesting that the heat advected over the ice sheet during the melt events is then retained near the surface by the clouds and the high atmospheric humidity. Thus, in both seasons, melt events are reinforced by a positive feedback resulting from increased longwave radiation, a process that was considered relevant during an

extreme melt episode in July 2012 (Bennartz et al., 2013; Neff et al., 2014; Bonne et al., 2015; Fausto et al., 2016). In summer, when the incoming solar radiation is large, the decrease in albedo (Fig. 5c) entails an additional positive feedback that can reinforce and prolong the melting (Box et al., 2012).").

[347] Sime L. C., *et al.* (2019) *Impact of abrupt sea ice loss on Greenland water isotopes during the last glacial period*, PROC. NAT'L. ACAD. SCI. 116(10):4099–4104, 4099 ("This is particularly important, since Dansgaard–Oeschger (DO) events are both the largest and best-documented examples of abrupt climate change (10–18).").

[348] Sime L. C., *et al.* (2019) *Impact of abrupt sea ice loss on Greenland water isotopes during the last glacial period*, PROC. NAT'L. ACAD. SCI. 116(10):4099–4104, 4099 ("Greenland ice cores provide excellent evidence of past abrupt climate changes. However, there is no universally accepted theory of how and why these Dansgaard–Oeschger (DO) events occur. Several mechanisms have been proposed to explain DO events, including sea ice, ice shelf buildup, ice sheets, atmospheric circulation, and meltwater changes. DO event temperature reconstructions depend on the stable water isotope ($\delta^{18}O$) and nitrogen isotope measurements from Greenland ice cores: interpretation of these measurements holds the key to understanding the nature of DO events. Here, we demonstrate the primary importance of sea ice as a control on Greenland ice core $\delta^{18}O$: 95% of the variability in $\delta^{18}O$ in southern Greenland is explained by DO event sea ice changes. Our suite of DO events, simulated using a general circulation model, accurately captures the amplitude of $\delta^{18}O$ enrichment during the abrupt DO event onsets. Simulated geographical variability is broadly consistent with available ice core evidence. We find an hitherto unknown sensitivity of the $\delta^{18}O$ paleothermometer to the magnitude of DO event temperature increase: the change in $\delta^{18}O$ per Kelvin temperature increase reduces with DO event amplitude. We show that this effect is controlled by precipitation seasonality.").

[349] Bierman P. R., *et al.* (2016) *A persistent and dynamic East Greenland Ice Sheet over the past 7.5 million years*, NATURE 540:256–260, 256 ("[M]aterial shed almost continuously from continents is preserved as marine sediment that can be analysed to infer the time-varying state of major ice sheets. Here we show that the East Greenland Ice Sheet existed over the past 7.5 million years, as indicated by beryllium and aluminium isotopes (^{10}Be and ^{26}Al) in quartz sand removed by deep, ongoing glacial erosion on land and deposited offshore in the marine sedimentary record.").

[350] Schaefer J. M., *et al.* (2016) *Greenland was nearly ice-free for extended periods during the Pleistocene*, NATURE 540:252–255, 253 ("Simulations of Greenland deglaciation in warm climates consistently predict the GISP2 site to be one of the last parts of the ice sheet to disappear; when it is ice-free, only a small ice cap in the eastern highlands remains, preserving old ice. This implies that when GISP2 bedrock was exposed to the surface cosmic-ray flux, more than 90% of the entire GIS was absent.").

[351] Schaefer J. M., *et al.* (2016) *Greenland was nearly ice-free for extended periods during the Pleistocene*, NATURE 540:252–255, 252 ("The GIS survived mid-Holocene temperatures somewhat warmer than those of the past millennium and many model simulations show a relatively stable GIS over the interglacials of the recent geologic past. However, simulations also show that the warming required to remove most of the GIS is model-dependent and sensitive to external forcings and internal feedbacks, including insolation forcing, accumulation rate parameterization, and distribution and seasonality of temperature. Results imply temperature thresholds for ice-sheet stability between one and a few degrees Celsius above present temperatures. Because the GIS sensitivity probably changes with increasing forcing temperature, model timescales for ice-sheet removal depend on the amplitude of the forcing: a temperature threshold of 2 °C with a 5,000-year response time given 3 °C warming was inferred by ref. 13, but more extreme temperature forcing allows for GIS removal within a few thousand or even several hundred years. Thus, current model results remain ambiguous but do show that both the magnitude and the duration of warmth are important to ice-sheet deglaciation.").

[352] Schaefer J. M., *et al.* (2016) *Greenland was nearly ice-free for extended periods during the Pleistocene*, NATURE 540:252–255, 254 ("To summarize, direct and robust evidence from the GISP2 bedrock core shows that the GIS was almost completely absent for an extended period of time during the Pleistocene. Our results do not directly determine the ice-dynamical processes responsible for the GIS deglaciation, but this first-order result is incompatible with many existing ice-sheet models or their respective climate-driving scenarios and provides important constraints for future simulations of past and future changes of the GIS. Models driven by boundary conditions appropriate to the warmest and most pronounced Pleistocene interglaciations must simulate the near-total disappearance of the ice sheet.").

[353] Pattyn F., *et al.* (2018) *The Greenland and Antarctic ice sheets under 1.5 ºC global warming*, NATURE CLIMATE CHANGE 8:1053–1061, 1056 ("The AIS has been losing mass since the mid-1990s, contributing 0.15–0.46 mm yr^{-1} s.l.e. on average between 1992 and 2017, accelerating to 0.49–0.73 mm yr^{-1} between 2012 and 2017. Observations over the past five years show that mass loss mainly occurs in the Antarctic Peninsula and West Antarctica (0.42–

0.65 mm yr^{-1} s.l.e.), with no significant contribution from East Antarctica (−0.01–0.16 mm yr^{-1} s.l.e.). The mass loss from the West Antarctic Ice Sheet (WAIS) is primarily caused by the acceleration of outlet glaciers in the Amundsen Sea Embayment (ASE), where the ice discharge of large outlet glaciers such as the Pine Island and Thwaites glaciers increased threefold since the early 1990s. However, this ASE mass loss is not a recent phenomenon, as ocean sediment records indicate that Pine Island Glacier experienced grounding-line retreat since approximately the 1940s.").

[354] Smith J. A., *et al.* (2017) *Sub-ice-shelf sediments record history of twentieth-century retreat of Pine Island Glacier*, NATURE 541:77–80, 77 ("Over the past 40 years, glaciers flowing into the Amundsen Sea sector of the ice sheet have thinned at an accelerating rate, and several numerical models suggest that unstable and irreversible retreat of the grounding line—which marks the boundary between grounded ice and floating ice shelf— is underway.").

[355] Favier L., *et al.* (2014) *Retreat of Pine Island Glacier controlled by marine ice-sheet instability*, NATURE CLIMATE CHANGE 4:117–121, 117 ("In recent years, the grounding line, which separates the grounded ice sheet from the floating ice shelf, has retreated by tens of kilometres. At present, the grounding line is crossing a retrograde bedrock slope that lies well below sea level, raising the possibility that the glacier is susceptible to the marine ice-sheet instability mechanism. Here, using three state-of-the-art ice-flow models, we show that Pine Island Glacier's grounding line is probably engaged in an unstable 40km retreat. The associated mass loss increases substantially over the course of our simulations from the average value of 20 Gt yr^{-1} observed for the 1992–2011 period, up to and above 100 Gt yr^{-1}, equivalent to 3.5–10 mm eustatic sea-level rise over the following 20 years. Mass loss remains elevated from then on, ranging from 60 to 120 Gt yr^{-1}.").

[356] Joughin I., *et al.* (2014) *Marine Ice Sheet Collapse Potentially Under Way for the Thwaites Glacier Basin, West Antarctica*, SCIENCE 344:735–738,735 ("Glaciers along the Amundsen Coast of Antarctica are thinning, producing the majority of Antarctica's contribution to sea-level rise. Much of this thinning is probably a response to the increased presence of warm modified Circumpolar Deep Water (CDW) on the adjacent continental shelf, which is melting and thinning the floating ice shelves that buttress the ice sheet."); *see also* Pattyn F., *et al.* (2018) *The Greenland and Antarctic ice sheets under 1.5 ºC global warming*, NATURE CLIMATE CHANGE 8:1053–1061, 1057 ("Major recent dynamic ice loss in the ASE is associated with high melt rates at the base of ice shelves that result from inflow of relatively warm Circumpolar Deep Water (CDW) in ice shelf cavities, which led to increased thinning of ice shelves in the area and to reduced buttressing of the grounded ice. Evidence from East Antarctica, as well as along the southern Antarctic Peninsula, also links glacier thinning and grounding-line retreat to CDW reaching the deep grounding lines.").

[357] Favier L., *et al.* (2014) *Retreat of Pine Island Glacier controlled by marine ice-sheet instability*, NATURE CLIMATE CHANGE 4:117–121, 117 ("Over the past 40 years Pine Island Glacier in West Antarctica has thinned at an accelerating rate, so that at present it is the largest single contributor to sea-level rise in Antarctica.").

[358] Favier L., *et al.* (2014) *Retreat of Pine Island Glacier controlled by marine ice-sheet instability*, NATURE CLIMATE CHANGE 4:117–121, 117 ("At present Pine Island Glacier (PIG) is responsible for 20% of the total ice discharge from the West Antarctic Ice Sheet (WAIS).").

[359] Jeong S., *et al.* (2016) *Accelerated ice shelf rifting and retreat at Pine Island Glacier, West Antarctica*, GEOPHYSICAL RESEARCH LETTERS 43:1–6, 1 ("Recent observations of continued acceleration, retreat, and thinning of Pine Island Glacier affirm its dynamic instability, suggesting that irreversible retreat has already begun [Rignot, 1998; Lee et al., 2012; Joughin et al., 2014; Rignot et al., 2014]. Observational analysis and ice flow models suggest that current degenerative change of Pine Island Glacier will persist for a century or more [Joughin et al., 2014; Rignot et al., 2014].").

[360] Joughin I., *et al.* (2014) *Marine Ice Sheet Collapse Potentially Under Way for the Thwaites Glacier Basin, West Antarctica*, SCIENCE 344:735–738,738 ("Our simulations provide strong evidence that the process of marine ice-sheet destabilization is already under way on Thwaites Glacier, largely in response to high subshelf melt rates. Although losses are likely to be relatively modest over the next century (<0.25 mm/year of sle), rapid collapse (>1 mm/year of sle) will ensue once the grounding line reaches the basin's deeper regions, which could occur within centuries. Such rapid collapse would probably spill over to adjacent catchments, undermining much of West Antarctica. Similar behavior also may be under way on neighboring Pine Island Glacier.").

[361] Jeong S., *et al.* (2016) *Accelerated ice shelf rifting and retreat at Pine Island Glacier, West Antarctica*, GEOPHYSICAL RESEARCH LETTERS 43:1–6, 1 ("Recent studies, however, have increasingly pointed toward ice-ocean interaction as the dominant driver [Shepherd et al., 2004; Jacobs et al., 2011; Liu et al., 2015]. In addition to increased thinning and grounding line retreat, over the past several decades, the Pine Island Glacier has undergone increased rifting and expansion of the lateral shear zones flanking the fast-flowing ice shelf [Bindschadler, 2002; MacGregor et al., 2012].").

[362] Rignot E., *et al.* (2014) *Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler glaciers, West Antarctica, from 1992 to 2011*, GEOPHYSICAL RESEARCH LETTERS 41:3502–3509, 3502 ("The grounding line is the critical boundary between grounded ice and the ocean which delineates where ice detaches from the bed and becomes afloat and frictionless at its base.").
[363] Alley K. E., *et al.* (2016) *Impacts of warm water on Antarctic ice shelf stability through basal channel formation*, NATURE GEOSCIENCE 9:290–293, 292 ("Our observations and statistical correlations between channel density, basal-melt rate, and grounding line depth suggest that ocean-sourced and grounding-line-sourced basal channel formation is primarily driven by [Circumpolar Deep Water], and that the channels can evolve on short timescales. The presence and growth of channels can cause structural ice-shelf-weakening along already-vulnerable shear zones, which leads us to suggest a possible future scenario in which ice-shelf basal channels could lead to large-scale destabilization through the reduction of ice-shelf back stress. With increased access of warm water beneath ice shelves and further incision of channels along shear margins, a tipping point could be reached where an ice shelf margin becomes disrupted enough to lead to increased calving, reduced ice shelf area, increased grounded ice flux, and accelerated sea-level rise. Although basal melting at the grounding line has already been shown to lead to increased ice flux, the implied additional mechanism of shear-margin weakening by basal channels could further accelerate grounded ice loss, a feedback that requires significant further exploration.").
[364] Alley K. E., *et al.* (2016) *Impacts of warm water on Antarctic ice shelf stability through basal channel formation*, NATURE GEOSCIENCE 9:290–293, 290–291 ("We found a significant positive correlation between basal channel density and basal-melt rate for all ice shelves ($p < 0.01$), suggesting that warm water plays an important role in the formation of these features. The Amundsen/Bellingshausen Sea (AB) sector, a region with generally high basal-melt rates due to Circumpolar Deep Water (CDW) presence, has a statistically higher density of basal channels than any other sector. Within this sector, there was also a significant positive correlation between basal channel density and maximum grounding line depth (calculated from the MOA 2009 grounding line and Bedmap2, $p < 0.05$). This correlation implies that CDW is responsible for creating these basal channels, as it is a mid-depth ocean water mass that mainly affects ice shelves with deep ice drafts.").
[365] Alley K. E., *et al.* (2016) *Impacts of warm water on Antarctic ice shelf stability through basal channel formation*, NATURE GEOSCIENCE 9:290–293,290 ("Antarctica's ice shelves provide resistance to the flow of grounded ice towards the ocean. If this resistance is decreased as a result of ice shelf thinning or disintegration, acceleration of grounded ice can occur, increasing rates of sea-level rise.").
[366] Alley K. E., *et al.* (2016) *Impacts of warm water on Antarctic ice shelf stability through basal channel formation*, NATURE GEOSCIENCE 9:290–293, 290 ("Loss of ice shelf mass is accelerating, especially in West Antarctica, where warm seawater is reaching ocean cavities beneath ice shelves. …The highest density of basal channels is found in West Antarctic ice shelves. Within the channels, warm water flows northwards, eroding the ice shelf base and driving channel evolution on annual to decadal timescales. Our observations show that basal channels are associated with the development of new zones of crevassing, suggesting that these channels may cause ice fracture. We conclude that basal channels can form and grow quickly as a result of warm ocean water intrusion, and that they can structurally weaken ice shelves, potentially leading to rapid ice shelf loss in some areas.").
[367] Favier L., *et al.* (2014) *Retreat of Pine Island Glacier controlled by marine ice-sheet instability*, NATURE CLIMATE CHANGE 4:117–121, 117 ("The recent retreat of PIG is now firmly attributed to acceleration of the glacier in response to sub-ice-shelf melting.").
[368] DeConto R. M. & Pollard D. (2016) *Contribution of Antarctica to past and future sea-level rise*, NATURE 531:591–597, 596 ("As in these prior studies, we also find that ocean-driven melt is an important driver of grounding-line retreat where warm water is in contact with ice shelves, but in scenarios with high greenhouse gas emissions we find that atmospheric warming soon overtakes the ocean as the dominant driver of Antarctic ice loss. Surface meltwater may lead to the ultimate demise of the major buttressing ice shelves and extensive grounding-line retreat, but it is the long thermal memory of the ocean that will inhibit the recovery of marine-based ice for thousands of years after greenhouse gas emissions are curtailed.").
[369] DeConto R. M. & Pollard D. (2016) *Contribution of Antarctica to past and future sea-level rise*, NATURE 531:591–597, 591 ("Today, extensive floating ice shelves in the Ross and Weddell Seas, and smaller ice shelves and ice tongues in the Amundsen and Bellingshausen seas provide buttressing that impedes the seaward flow of ice and stabilizes marine grounding zones. … Because the flux of ice across the grounding line increases strongly as a function of its thickness, initial retreat onto a reverse-sloping bed (where the bed deepens and the ice thickens upstream) can trigger a runaway Marine Ice Sheet Instability (MISI).").
[370] Jeong S., *et al.* (2016) *Accelerated ice shelf rifting and retreat at Pine Island Glacier, West Antarctica*, GEOPHYSICAL RESEARCH LETTERS 43:1–6, 1 ("While the most recent (2011) rifting and calving event initiated

further inland than the two prior events [Bindschadler and Rignot, 2001; Howat et al., 2012], the net change in ice front position was small, with little resulting change to the ice shelf's structure. Further, following a sustained acceleration [Lee et al., 2012] coinciding with ungrounding of its terminal ice plain [Rignot et al., 2014], ice shelf velocities stabilized and slightly decreased between 2009 and 2013, suggesting that the ice shelf may have reached a new, if temporary, stable terminus position. However, two anomalous rifts appeared in late 2014 and early 2015 that, in contrast to previous events, initiated in the center of the ice shelf and propagated toward the margins.").

[371] Jeong S., *et al.* (2016) *Accelerated ice shelf rifting and retreat at Pine Island Glacier, West Antarctica*, GEOPHYSICAL RESEARCH LETTERS 43:1–6, 4 ("The style of ice shelf rifting currently underway at the Pine Island Glacier is fundamentally different from previous episodes of rifting and calving in the last decade, in which preexisting, marginal rifts propagated from the seaward end of the northern shear margin across the tongue, perpendicular to the mean flow direction. The initiation of multiple rifts in the center of a fast-flowing (faster than 1 km/yr) ice shelf is unusual.").

[372] Smith J. A., *et al.* (2017) *Sub-ice-shelf sediments record history of twentieth-century retreat of Pine Island Glacier*, NATURE 541:77–80, 77 ("Here we show that the present thinning and retreat of Pine Island Glacier in West Antarctica is part of a climatically forced trend that was triggered in the 1940s. Our conclusions arise from analysis of sediment cores recovered beneath the floating Pine Island Glacier ice shelf, and constrain the date at which the grounding line retreated from a prominent seafloor ridge. We find that incursion of marine water beyond the crest of this ridge, forming an ocean cavity beneath the ice shelf, occurred in 1945 (±12 years); final ungrounding of the ice shelf from the ridge occurred in 1970 (±4 years). The initial opening of this ocean cavity followed a period of strong warming of West Antarctica, associated with El Niño activity. Thus our results suggest that, even when climate forcing weakened, ice-sheet retreat continued.").

[373] Smith J. A., *et al.* (2017) *Sub-ice-shelf sediments record history of twentieth-century retreat of Pine Island Glacier*, NATURE 541:77–80, 79–80 ("Our findings have implications for understanding the controls on ice-sheet retreat. Although our results support the inference that the PIG ice shelf finally unpinned from the transverse ridge in the early 1970s, we observe that the ocean cavity just inland of the seafloor ridge first opened up to ocean waters around 1945, shortly after notable El Niño conditions between 1939 and 1942 and after observed warming in West Antarctica between 1936 and 1945. At this time, the ice was still firmly grounded on the highest parts of the ridge, where it may have been grounded since the early Holocene. But it must have lifted off towards the south to allow an ocean cavity to develop upstream of the still grounded parts, first allowing coarse-grained deposition, then—as the ocean cavity enlarged and the grounding line retreated about 1.5 km inland of PIG B—allowing fine-grained sediments to accumulate. The ice remained in contact with the highest parts of the ridge, bulldozing sediment off the ridge crest and down the seaward slope until the early 1970s, consistent with interpretations of the earliest Landsat imagery.").

[374] Smith J. A., *et al.* (2017) *Sub-ice-shelf sediments record history of twentieth-century retreat of Pine Island Glacier*, NATURE 541:77–80, 80 ("Despite a return to pre-1940s climatic conditions in the ensuing decades, thinning and glacier retreat has not stopped and is unlikely to be reversible without a major change in marine or glaciological conditions. Thus, a period of warming in the Antarctic shelf waters triggered a substantial change in the ice sheet, via the mechanism that we see today—that is, ocean-driven thinning and retreat of ice shelves leads to inland glacier acceleration and ice-sheet thinning. Notably, our findings also suggest that ice-sheet retreat can continue even when the forcing reverts to its earlier state.").

[375] Strauss B. H., *et al.* (2015) *Carbon choices determine US cities committed to futures below sea level*, PROC. NAT'L. ACAD. SCI. 112(44):13508–13513, 13510 ("Remote sensing studies indicate accelerating decay, plus bedrock topography favorable to collapse, for the Thwaites and Pine Island glaciers, two linchpins of the WAIS. Recent modeling work also points toward future collapse, even at reduced rates of warming and decay from the present. Topographic analysis together with theory and expert judgment indicate that the highly interconnected marine component of West Antarctica is prone to marine ice sheet instability that would spread throughout the entire basin following the disintegration of the Thwaites and Pine Island glaciers.").

[376] Li X., *et al.* (2015) *Grounding line retreat of Totten Glacier, East Antarctica, 1996 to 2013*, GEOPHYSICAL RESEARCH LETTERS 42:8049–8056, 8049 ("Totten Glacier (TG), the largest discharger of ice in East Antarctica [Rignot, 2006], drains a sector 537,900 km^2 in size, mostly grounded below sea level….").

[377] Li X., *et al.* (2015) *Grounding line retreat of Totten Glacier, East Antarctica, 1996 to 2013*, GEOPHYSICAL RESEARCH LETTERS 42:8049–8056, 8055 ("The ongoing grounding line retreat of TG, about 1 – 3 ± 0.1 km in 17 years, is 1 order magnitude smaller than that observed in the Amundsen Sea sector of West Antarctica, at around 1–2 km/yr [Rignot et al., 2014], and we find no retrograde channels in the immediate vicinity of the grounding line of TG that would accelerate the rate of grounding line retreat. Yet TG hosts 4 times the sea level equivalent of the

Amundsen Sea sector so that any amount of grounding retreat of TG may still bare significant consequences for sea level rise from Antarctica.").

[378] Li X., *et al.* (2015) *Grounding line retreat of Totten Glacier, East Antarctica, 1996 to 2013*, GEOPHYSICAL RESEARCH LETTERS 42:8049–8056, 8049 ("TG holds an ice volume equivalent to 3.9 m global sea level rise, comparable to the West Antarctic Ice Sheet [Fretwell et al., 2013; Bamber et al., 2009]. Its mass flux into the ocean of 71 ± 3 Gt/yr in 2007–2008 was out of balance with its long-term (1979–2004) average mass input from snowfall of 67 ± 3 Gt/yr [Rignot et al., 2013; Lenaerts and van den Broeke, 2012]; i.e., the glacier has been losing mass [Rignot and Thomas, 2002; Rignot, 2008].").

[379] Li X., *et al.* (2016) *Ice flow dynamics and mass loss of Totten Glacier, East Antarctica, from 1989 to 2015*, GEOPHYSICAL RESEARCH LETTERS 43:6366–6373, 6366 ("A recent analysis showed that the glacier grounding line retreated by 1 to 3 km between 1996 and 2013, corresponding to an average ice thinning rate of 0.7 ± 0.1 m/yr [Li et al., 2015]. This magnitude thinning is consistent with the altimetry record and suggests that ice has been flowing faster than the speed required to maintain a state of mass balance with snowfall in the interior region.").

[380] Li X., *et al.* (2016) *Ice flow dynamics and mass loss of Totten Glacier, East Antarctica, from 1989 to 2015*, GEOPHYSICAL RESEARCH LETTERS 43:6366–6373, 6371 ("We attribute the changes in ice dynamics to oceanic forcing because field observations have shown the presence of mCDW on the continental shelf near Totten [Bindoff et al., 2000; Williams et al., 2011]. Warm mCDW fuels high melt rates in this area, and a change in ocean temperature is the most likely explanation for the observed change in ice dynamics. Sea floor bathymetry from gravity inversion reveals the presence of a valley crossing the main sill in front of the glacier that is deeper than the thermocline depth [Blankenship et al., 2015]. This valley may allow access of warm modified Circumpolar Deep Water (mCDW) to the sub–ice shelf cavity and induce rapid ice shelf melting. The main stream is grounded >2300 m below sea level at the grounding line, which is the deepest part of the sub–ice shelf cavity. Ice shelf melt rates are expected to be highest in this region due to the pressure dependence of the freezing point of seawater. …Grounding line retreat has also been observed [Li et al., 2015]. The reanalysis temperature data from ECCO2 solution indicate three periods of warming/cooling of the subsurface water (450 – 600 m depth) on the continental shelf, which agree with periods of acceleration/deceleration of the glacier. If this is correct, this indicates a significant sensitivity of the glacier to ocean temperature, which is consistent with the presence of an ice plain in the grounding line region [Li et al., 2015]. Coastal polynya activities can cause short-term variability in subglacial melt rates by modulating mCDW access into the sub – ice shelf cavity [Khazendar et al., 2013; Gwyther et al., 2014].").

[381] Greenbaum J. S., *et al.* (2015) *Ocean access to a cavity beneath Totten Glacier in East Antarctica*, NATURE GEOSCIENCE 8:294–298, 297 ("[W]e expect the water column thickness over the trough to increase by several metres per year to maintain hydrostatic equilibrium if thinning trends continue. This could allow additional exchange between the TGIS and the ocean, accelerate ice-shelf thinning, and allow grounded ice to accelerate towards the coast. The availability of MCDW and recent accelerated mass loss support the idea that the behaviour of Totten Glacier is an East Antarctic analogue to ocean-driven retreat underway in the West Antarctic Ice Sheet (WAIS). The global sea level potential of 3.5 m flowing through Totten Glacier alone is of similar magnitude to the entire probable contribution of the WAIS. As with the WAIS, much of the broader drainage basin accessible to a retreating Totten Glacier is grounded below sea level, with a potential contribution of 5.1 m, so instabilities from ice–ocean interaction in East Antarctica could have significant global consequences.").

[382] Greenbaum J. S., *et al.* (2015) *Ocean access to a cavity beneath Totten Glacier in East Antarctica*, NATURE GEOSCIENCE 8:294–298, 294 ("Totten Glacier, the primary outlet of the Aurora Subglacial Basin, has the largest thinning rate in East Antarctica.").

[383] Li X., *et al.* (2016) *Ice flow dynamics and mass loss of Totten Glacier, East Antarctica, from 1989 to 2015*, GEOPHYSICAL RESEARCH LETTERS 43:6366–6373, 6371–6372 ("We assembled a 26 year long time series of ice velocity measurements on Totten Glacier to conclude that the glacier speed has fluctuated up to 18% during the time period, with low values around 2000, high values prior to 1996 and after 2002. In the last 10 years, the glacier has maintained a relatively steady speed but has been flowing above equilibrium conditions. The glacier has been losing mass at a rate of 6.8 ± 2.4 Gt/yr or 10% of the total flux on average for the past 26 years. The main loss is caused by the speedup of the glacier along its main flow. Our results also suggest that the glacier may be strongly sensitive to ocean temperature. More detailed studies are needed to quantify the impact of ocean temperature on ice dynamics in this important sector of East Antarctica.").

[384] Lenaerts J. T. M., *et al.* (2017) *Meltwater produced by wind–albedo interaction stored in an East Antarctic ice shelf*, NATURE CLIMATE CHANGE 7:58–62, 58 ("Unlike the Antarctic Peninsula, where foehn events originate from episodic interaction of the circumpolar westerlies with the topography, in coastal East Antarctica high temperatures are caused by persistent katabatic winds originating from the ice sheet's interior. Katabatic winds warm and mix the

air as it flows downward and cause widespread snow erosion, explaining >3 K higher near-surface temperatures in summer and surface melt doubling in the grounding zone compared with its surroundings. Additionally, these winds expose blue ice and firn with lower surface albedo, further enhancing melt. The *in situ* observation of supraglacial flow and englacial storage of meltwater suggests that ice-shelf grounding zones in East Antarctica, like their Antarctic Peninsula counterparts, are vulnerable to hydrofracturing.”).

[385] Lenaerts J. T. M., *et al.* (2017) *Meltwater produced by wind–albedo interaction stored in an East Antarctic ice shelf*, NATURE CLIMATE CHANGE 7:58–62, 61 (“Historical visible satellite imagery and climate model output demonstrate that surface melt has occurred on the RBIS since the start of the observational record (1980s), but only during warm summers. No trend is visible over this period (Supplementary Fig. 5). The high correlation between regional near-surface summer temperature and melt (R^2 =0.7, Supplementary Fig. 5) suggests that meltwater production and subsequent storage and drainage will increase in the future, when warm summers are projected to be more prevalent. In combination with constant katabatic winds, this would further deplete firn pore space near these grounding lines, amplifying the risk of ice-shelf collapse and subsequent rapid ice loss from East Antarctica.”).

[386] Golledge N. R., *et al.* (2015) *The multi-millennial Antarctic commitment to future sea-level rise*, NATURE 526:421–425, 421 (“Atmospheric warming is projected to increase global mean surface temperatures by 0.3 to 4.8 degrees Celsius above pre-industrial values by the end of this century. If anthropogenic emissions continue unchecked, the warming increase may reach 8–10 degrees Celsius by 2300 (ref. 2). The contribution that large ice sheets will make to sea-level rise under such warming scenarios is difficult to quantify because the equilibrium-response timescale of ice sheets is longer than those of the atmosphere or ocean. Here we use a coupled ice-sheet/ice-shelf model to show that if atmospheric warming exceeds 1.5 to 2 degrees Celsius above present, collapse of the major Antarctic ice shelves triggers a centennial- to millennial-scale response of the Antarctic ice sheet in which enhanced viscous flow produces a long-term commitment (an unstoppable contribution) to sea-level rise. Our simulations represent the response of the present-day Antarctic ice-sheet system to the oceanic and climatic changes of four representative concentration pathways (RCPs) from the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. We find that substantial Antarctic ice loss can be prevented only by limiting greenhouse gas emissions to RCP 2.6 levels. Higher-emissions scenarios lead to ice loss from Antarctic that will raise sea level by 0.6–3 metres by the year 2300. Our results imply that greenhouse gas emissions in the next few decades will strongly influence the long-term contribution of the Antarctic ice sheet to global sea level.”).

[387] Rignot E., *et al.* (2019) *Four decades of Antarctic Ice Sheet mass balance from 1979–2017*, PROC. NAT’L. ACAD. SCI. 116(4):1095–1103, 1100 (“In total, the mass loss of West Antarctica is dominated by a sector spanning from George VI to Land glaciers, about 2,400 km in length, with 92% of the signal from the ASE. West Antarctica contributed 6.9 ± 0.6-mm SLR since 1979.”).

[388] Rignot E., *et al.* (2019) *Four decades of Antarctic Ice Sheet mass balance from 1979–2017*, PROC. NAT’L. ACAD. SCI. 116(4):1095–1103, 1101 (“In total, the mass loss in East Antarctica is dominated by Wilkes Land, with a total contribution of 4.4 ± 0.9-mm SLR since 1979.”).

[389] DeConto R. M. & Pollard D. (2016) *Contribution of Antarctica to past and future sea-level rise*, NATURE 531:591–597, 595 (“Importantly, the ensemble analysis supports our choice of ‘default’ model parameters used in the nominal Pliocene, LIG, and future simulations. The lack of substantial ice-sheet retreat in the optimistic RCP2.6 scenario remains unchanged, but the Large Ensemble analysis substantially increases our RCP4.5 and RCP8.5 2100 sea-level projections to 49 ± 20 cm and 105 ± 30 cm, if higher (>10 m instead of >5 m) Pliocene sea-level targets are used. Adding the ocean temperature correction in the Amundsen and Bellingshausen seas further increases the 2100 projections in RCP2.6, RCP4.5 and RCP8.5 to 16±16cm, 58±28cm and 114±36cm, respectively.”).

[390] DeConto R. M. & Pollard D. (2016) *Contribution of Antarctica to past and future sea-level rise*, NATURE 531:591–597, 593 (“The RCP scenarios (Fig. 4) produce a wide range of future Antarctic contributions to sea level, with RCP2.6 producing almost no net change by 2100, and only 20 cm by 2500. Conversely, RCP4.5 causes almost complete WAIS collapse within the next five hundred years, primarily owing to the retreat of Thwaites Glacier into the deep WAIS interior. … In RCP4.5, GMSL rise is 32 cm by 2100, but subsequent retreat of the WAIS interior, followed by the fringes of the Wilkes Basin and the Totten Glacier/Law Dome sector of the Aurora Basin produces 5 m of GMSL rise by 2500.”).

[391] DeConto R. M. & Pollard D. (2016) *Contribution of Antarctica to past and future sea-level rise*, NATURE 531:591–597, 593–549 (“In RCP8.5, increased precipitation causes an initial, minor gain in total ice mass, but rapidly warming summer air temperatures trigger extensive surface meltwater production and hydrofracturing of ice shelves by the middle of this century. The Larsen C is one of the first shelves to be lost, about 2055. … Massive meltwater production on shelf surfaces, and eventually on the flanks of the ice sheet, would quickly overcome the buffering capacity of firn. In the model, the meltwater accelerates WAIS retreat via its thermomechanical influence

on ice rheology and the influence of hydrofacturing on crevassing and structural failure of the retreating margin. Antarctica contributes 77 cm of GMSL rise by 2100, and continued loss of the Ross and Weddell Sea ice shelves drives WAIS retreat from three sides simultaneously. …As a result, WAIS collapses within 250 years. At the same time, steady retreat into the Wilkes and Aurora basins, where the ice above floatation is >2,000 m thick, adds substantially to the rate of sea-level rise, exceeding 4 cm yr^{-1} in the next century, which is comparable to maximum rates of sea-level rise during the last deglaciation. At 2500, GMSL rise for the RCP8.5 scenario is 12.3 m. As in our LIG simulations, atmosphere–ice sheet coupling accounting for the warming feedback associated with the retreating ice sheet adds an additional 1.3 m of GMSL to the RCP8.5 scenario.").

[392] Konrad H., *et al.* (2018) *Net retreat of Antarctic glacier grounding lines*, NATURE GEOSCIENCE 11:258–262, 258 ("In Antarctica, grounding lines are of particular interest because ice-shelf thinning and collapse have driven grounding-line retreat and glacial imbalance around the continent. Although Antarctic grounding lines have retreated since the Last Glacial Maximum, the pace of retreat at several Antarctic ice streams has been much higher during the satellite era and numerical simulations have indicated that this rapid retreat may be followed by centennial-scale collapse of the inland catchment areas.").

[393] Reese R., *et al.* (2017) *The far reach of ice-shelf thinning in Antarctica*, NATURE CLIMATE CHANGE 8:53–57, 53 ("Floating ice shelves, which fringe most of Antarctica's coastline, regulate ice flow into the Southern Ocean. Their thinning or disintegration can cause upstream acceleration of grounded ice and raise global sea levels. So far the effect has not been quantified in a comprehensive and spatially explicit manner. Here, using a finite-element model, we diagnose the immediate, continent-wide flux response to different spatial patterns of ice-shelf mass loss. We show that highly localized ice-shelf thinning can reach across the entire shelf and accelerate ice flow in regions far from the initial perturbation. As an example, this 'tele-buttressing' enhances outflow from Bindschadler Ice Stream in response to thinning near Ross Island more than 900 km away. We further find that the integrated flux response across all grounding lines is highly dependent on the location of imposed changes: the strongest response is caused not only near ice streams and ice rises, but also by thinning, for instance, well-within the Filchner–Ronne and Ross Ice Shelves. The most critical regions in all major ice shelves are often located in regions easily accessible to the intrusion of warm ocean waters, stressing Antarctica's vulnerability to changes in its surrounding ocean.").

[394] Pollard D., *et al.* (2015) *Potential Antarctic Ice Sheet retreat driven by hydrofracturing and ice cliff failure*, EARTH & PLANETARY SCIENCE LETTERS 412:112–121, 112 ("Here, we use a continental ice sheet model to show that mechanisms based on recent observations and analysis have the potential to resolve this model–data conflict. In response to atmospheric and ocean temperatures typical of past warm periods, floating ice shelves may be drastically reduced or removed completely by increased oceanic melting, and by hydrofracturing due to surface melt draining into crevasses. Ice at deep grounding lines may be weakened by hydrofracturing and reduced buttressing, and may fail structurally if stresses exceed the ice yield strength, producing rapid retreat. Incorporating these mechanisms in our ice-sheet model accelerates the expected collapse of the West Antarctic Ice Sheet to decadal time scales, and also causes retreat into major East Antarctic subglacial basins, producing ~17 m global sea-level rise within a few thousand years."); *see also* Pattyn F., *et al.* (2018) *The Greenland and Antarctic ice sheets under 1.5 ºC global warming*, NATURE CLIMATE CHANGE 8:1053–1061, 1057 ("Reduction of buttressing of ice shelves via the processes described above may eventually lead to the so-called marine ice sheet instability (MISI; Fig. 3). For the WAIS, where the bedrock lies below sea level and slopes down towards the interior of the ice sheet, MISI may lead to a (partial) collapse of this marine ice sheet. This process, first hypothesized in the 1970s, was recently theoretically confirmed and demonstrated in numerical models. It arises from thinning and eventually flotation of the ice near the grounding line, which moves the latter into deeper water where the ice is thicker. Thicker ice results in increased ice flux, which further thins (and eventually floats) the ice, resulting in further retreat into deeper water (and thicker ice) and so on. The possibility that some glaciers, such as Pine Island Glacier and Thwaites Glacier, are already undergoing MISI has been suggested by numerical simulations using state-of-the-art ice-sheet models. The past retreat (up to 2010) of Pine Island Glacier has been attributed to MISI triggered by oceanic forcing, although its recent slowdown may be due to a combination of abated forcing and a concomitant increase in glacier buttressing. Thwaites Glacier is currently in a less-buttressed state, and several simulations using state-of-the-art ice sheet models indicate continued mass loss and possibly MISI even under present climatic conditions.").

[395] Pollard D., *et al.* (2015) *Potential Antarctic Ice Sheet retreat driven by hydrofracturing and ice cliff failure*, EARTH & PLANETARY SCIENCE LETTERS 412:112–121, 113 ("In contrast to WAIS, most of the EAIS is grounded above sea level and is not directly vulnerable to ocean warming. The EAIS first attained full continental size at the Eocene–Oligocene boundary (Pusz et al., 2011; DeConto and Pollard, 2003). The atmospheric warming necessary to produce substantial retreat from continental size in previous ice-climate model simulations is considerable, ~15 to

20 ºC (Huybrechts, 1993) or atmospheric CO_2 levels of ~4× to 9× PAL (Preindustrial Atmospheric Level, 280 ppmv) (Pollard and DeConto, 2005).").

[396] Pollard D., *et al.* (2015) *Potential Antarctic Ice Sheet retreat driven by hydrofracturing and ice cliff failure*, EARTH & PLANETARY SCIENCE LETTERS 412:112–121, 116 ("As expected, West Antarctica undergoes major collapse driven primarily by increased sub-ice melt from the +2 ºC ocean warming, causing reduced buttressing at the major WAIS grounding lines, and leading to classic marine instability (MISI) into the deepening interior beds (Weertman, 1974; Schoof, 2007). The time scale of this retreat is several hundred to a thousand years (Pollard and DeConto, 2009, and Fig. 4, cyan curve).").

[397] National Snow & Ice Data Center (NSIDC), *All About Sea Ice: Arctic vs. Antarctic* (*last accessed* 16 October 2017) ("Sea ice differs between the Arctic and Antarctic, primarily because of their different geography. The Arctic is a semi-enclosed ocean, almost completely surrounded by land. As a result, the sea ice that forms in the Arctic is not as mobile as sea ice in the Antarctic. … The Antarctic is almost a geographic opposite of the Arctic, because Antarctica is a land mass surrounded by an ocean. The open ocean allows the forming sea ice to move more freely, resulting in higher drift speeds. However, Antarctic sea ice forms ridges much less often than sea ice in the Arctic. Also, because there is no land boundary to the north, the sea ice is free to float northward into warmer waters where it eventually melts. As a result, almost all of the sea ice that forms during the Antarctic winter melts during the summer.").

[398] National Snow & Ice Data Center (NSIDC), *All About Sea Ice: Arctic vs. Antarctic* (*last accessed* 16 October 2017) ("Because sea ice does not stay in the Antarctic as long as it does in the Arctic, it does not have the opportunity to grow as thick as sea ice in the Arctic. While thickness varies significantly within both regions, Antarctic ice is typically 1 to 2 meters (3 to 6 feet) thick, while most of the Arctic is covered by sea ice 2 to 3 meters (6 to 9 feet) thick. Some Arctic regions are covered with ice that is 4 to 5 meters (12 to 15 feet) thick.").

[399] National Snow & Ice Data Center (NSIDC), *All About Sea Ice: Arctic vs. Antarctic* (*last accessed* 16 October 2017) ("Antarctic sea ice does not reach the South Pole, extending only to about 75 degrees south latitude (in the Ross and Weddell Seas), because of the Antarctic continent. However, Arctic sea ice can extend all the way to the North Pole. Here, the Arctic sea ice receives less solar energy at the surface because the sun's rays strike at a more oblique angle, compared to lower latitudes.").

[400] National Snow & Ice Data Center (NSIDC) *2014 melt season in review* (7 October 2014) ("As we reported in our Arctic minimum announcement, sea ice in Antarctica has remained at satellite-era record high daily levels for most of 2014. On September 22, 2014, Antarctic ice extent increased to 20.11 million square kilometers (7.76 million square miles). This was the likely maximum extent for the year. This year's Antarctic sea ice maximum was 1.54 million square kilometers (595,000 square miles) above the 1981 to 2010 average maximum extent, which is nearly four standard deviations above this average. The 2014 ice extent record is 560,000 square kilometers (216,000 square miles) above the previous record ice extent set on October 1, 2013. Each of the last three years (2012, 2013, and 2014) has set new record highs for extent in the Antarctic. The monthly average Antarctic ice extent for September 2014 is 20.03 million square kilometers (7.73 million square miles). This is 1.24 million square kilometers (479,000 square miles) above the 1981 to 2010 average for September ice extent. The Antarctic sea ice trend for September is now +1.3% per decade relative to the 1981 to 2010 average.").

[401] National Snow & Ice Data Center (NSIDC) *Arctic sea ice 2017: Tapping the brakes in September* (5 October 2017) ("Antarctic sea ice may have reached its maximum extent on September 15, at 17.98 million square kilometers (6.94 million square miles), among the earliest maxima on record. If this date and extent hold, it will be the second-lowest daily maximum in the satellite record, 20,000 square kilometers (7,700 square miles) above 1986. Antarctic sea ice extent has been at record or near-record lows since September 2016. A series of recent studies have explored causes of the sudden decline in extent that occurred in austral late winter and spring of 2016. Most studies conclude that an unusual period of strong meridional winds—consistent with a very pronounced negative phase of the Southern Annular Mode index, coupled with a significant 'wave-3 pattern' in the atmospheric circulation—were the cause. A 'wave-3 pattern' refers to a tendency for circulation around the southern continent to resemble a three-leaf clover, rather than the more typical near-zonal (along lines of longitude) pattern.").

[402] National Snow & Ice Data Center (NSIDC) *Arctic summer 2018: September extent ties for sixth lowest* (8 October 2018) ("This year's maximum date of October 2 is about nine days later than the 1981 to 2010 median date and ten days later than the 1981 to 2010 average date.").

[403] National Snow & Ice Data Center (NSIDC) *Arctic summer 2018: September extent ties for sixth lowest* (8 October 2018) ("Antarctic sea ice may have reached its maximum extent on October 2, 2018, at 18.15 million square kilometers (7.01 million square miles). If the downward trend continues, it will be the fourth lowest

maximum in the satellite record—higher than the 1986, 2002, and 2017 maxima. It is 180,000 square kilometers (70,000 square miles) above the record low Antarctic maximum set in 1986, at 17.97 million square kilometers (6.94 million square miles). It is also 560,000 square kilometers (216,000 square miles) below the 1981 to 2010 average maximum extent of 18.71 million square kilometers (7.22 million square miles).").

[404] National Snow & Ice Data Center (NSIDC) *Arctic sea ice maximum at record low for third straight year* (22 March 2017) ("In the Southern Hemisphere, sea ice likely reached its minimum extent for the year on March 3, at 2.11 million square kilometers (815,000 square miles). This year's minimum extent was the lowest in the satellite record, continuing a period of satellite-era record low daily extents that began in early November. However, the Antarctic system has been highly variable. As recently as 2015, Antarctic sea ice set record high daily extents, and in September 2014 reached a record high winter maximum.").

[405] National Snow & Ice Data Center (NSIDC) *Arctic sea ice maximum at record low for third straight year* (22 March 2017) ("The Antarctic minimum extent is 740,000 square kilometers (286,000 square miles) below the 1981 to 2010 average minimum of 2.85 million square kilometers (1.10 million square miles) and 184,000 square kilometers (71,000 square miles) below the previous lowest minimum that occurred on February 27, 1997.").

[406] National Snow & Ice Data Center (NSIDC) *Arctic sea ice maximum at record low for third straight year* (22 March 2017) ("Antarctic air temperatures during the autumn and winter were above average, but less so than in the Arctic. Air temperatures at the 925 hPa level (about 2,500 feet above sea level) near the sea ice edge have been about 1 to 2.5 degrees Celsius (2 to 4.5 degrees Fahrenheit) above the 1981 to 2010 average.").

[407] National Snow & Ice Data Center (NSIDC) *Another record, but a somewhat cooler Arctic Ocean* (11 April 2017) ("Following the record-low seasonal sea ice minimum, Antarctic sea ice extent has sharply risen, but extent is still far below average, and set daily record low values throughout the month of March. Regionally, sea ice recovered to near average conditions in the Weddell Sea and around much of the coast of East Antarctica. The primary region of below average extent was in the Ross, Amundsen, and Bellingshausen Sea regions, as has been the case throughout the spring and summer. This appears to be related to warmer-than-average sea surface temperatures.").

[408] National Snow & Ice Data Center (NSIDC) *Ho hum February it may be, unless we speak of the Bering Sea* (4 March 2019) ("After plummeting in late December to record daily lows in sea ice extent, Antarctica's melt slowed significantly in January and February, reaching its likely minimum of 2.47 million square kilometers (954,000 square miles) on both February 28 and March 1. This is the seventh lowest extent in the satellite record.").

[409] 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, 14245 ("The observed increase in the concentration of greenhouse gases (GHGs) since the preindustrial era has most likely committed the world to a warming of 2.4ºC (1.4ºC to 4.3ºC) above the preindustrial surface temperatures. …The estimated warming of 2.4ºC is the equilibrium warming above preindustrial temperatures that the world will observe even if GHG concentrations are held fixed at their 2005 concentration levels but without any other anthropogenic forcing such as the cooling effect of aerosols. …IPCC models suggest that ≈25% (0.6ºC) of the committed warming has been realized as of now. About 90% or more of the rest of the committed warming of 1.6ºC will unfold during the 21st century, determined by the rate of the unmasking of the aerosol cooling effect by air pollution abatement laws and by the rate of release of the GHGs-forcing stored in the oceans. The accompanying sea-level rise can continue for more than several centuries."); *see also* Ramanathan V. & Xu Y. (2010) *The Copenhagen Accord for limiting global warming: criteria, constraints, and available avenues*, PROC. NAT'L. ACAD. SCI. 107(18):8055–8062, 8056, Box 2 Figure.

[410] Arctic Monitoring and Assessment Programme (2011) SNOW, WATER, ICE AND PERMAFROST IN THE ARCTIC, EXECUTIVE SUMMARY AND KEY MESSAGE, 4 ("The increase in annual average temperature since 1980 has been twice as high over the Arctic as it has been over the rest of the world.").

[411] Serreze M. C. & Barry R. G. (2011) *Processes and impacts of Arctic amplification: A research synthesis*, GLOBAL PLANET CHANGE 77:85–96, 85 ("Arctic amplification is now recognized as an inherent characteristic of the global climate system, with multiple intertwined causes operating on a spectrum of spatial and temporal scales. These include, but are not limited to, changes in sea ice extent that impact heat between the ocean and the atmosphere, atmospheric and oceanic heat transports, cloud cover and water vapor that alter the longwave radiation flux to the surface, soot on snow and heightened black carbon aerosol concentrations. Strong warming over the Arctic Ocean during the past decade in autumn and winter, clearly associated with reduced sea ice extent, is but the most recent manifestation of the phenomenon. Indeed, periods of Arctic amplification are evident from analysis of both warm and cool periods over at least the past three million years. Arctic amplification being observed today is expected to become stronger in coming decades, invoking changes in atmospheric circulation, vegetation and the carbon cycle, with impacts both within and beyond the Arctic.").

[412] Allen M., *et al.* (2018) SUMMARY FOR POLICYMAKERS, *in* IPCC (2018) GLOBAL WARMING OF 1.5 ºC, 6 ("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*)").

[413] 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):10,315–10,323, 10315 ("With unchecked emissions, the central warming can reach the dangerous level within three decades, with the LPHI warming becoming catastrophic by 2050. We outline a three-lever strategy to limit the central warming below the dangerous level and the LPHI below the catastrophic level, both in the near term (<2050) and in the long term (2100): the carbon neutral (CN) lever to achieve zero net emissions of CO_2, the super pollutant (SP) lever to mitigate short-lived climate pollutants, and the carbon extraction and sequestration (CES) lever to thin the atmospheric CO_2 blanket. Pulling on both CN and SP levers and bending the emissions curve by 2020 can keep the central warming below dangerous levels. To limit the LPHI warming below dangerous levels, the CES lever must be pulled as well to extract as much as 1 trillion tons of CO_2 before 2100 to both limit the preindustrial to 2100 cumulative net CO_2 emissions to 2.2 trillion tons and bend the warming curve to a cooling trend.").

[414] Zeebe R. E., *et al.* (2016) *Anthropogenic carbon release rate unprecedented during the past 66 million years*, NATURE GEOSCIENCE 9:325–329, 325 ("The climate response is not instantaneous, but rather shows a characteristic temporal delay depending on the climate system's thermal inertia. For instance, the rate at which Earth's surface temperature approaches a new equilibrium depends critically on the ocean's heat uptake efficiency. Whereas the initial few percent of the response may be achieved within decades, the final few percent can take up to millennia.").

[415] Tanaka K. & O'Neill B. C. (2018) *The Paris Agreement zero-emissions goal is not always consistent with the 1.5 °C and 2 °C temperature targets*, NATURE CLIMATE CHANGE 8:319–324, 320 ("We find that remaining below either 1.5 °C or 2 °C does not require GHG emissions to be reduced to a net zero level (Cases II and IV) (Fig. 1). These results are based on default model assumptions, except that in order to make achieving the 1.5°C target feasible (Case II), we had to allow for extremely rapid mitigation by relaxing the abatement rate constraints (that is, first derivative constraint changed from 4%/year to 8%/year and second derivative constraint removed, see Methods). In the least-cost emissions pathway, net GHG emissions fall to approximately 10 $GtCO_2eq$/year in about 2033 in the 1.5°C case and to 16 $GtCO_2eq$/year in about 2060 in the 2°C case, and then remain nearly constant after that.").

[416] Tanaka K. & O'Neill B. C. (2018) *The Paris Agreement zero-emissions goal is not always consistent with the 1.5 °C and 2 °C temperature targets*, NATURE CLIMATE CHANGE 8:319–324, 323 ("Thus a zero-emissions target for CO_2, rather than GHGs, is more likely to be consistent with the Paris temperature targets, unless either (i) overshoot of the temperature targets were allowed, or (ii) the intent of the Paris Agreement is not only to keep warming from exceeding a given level but to then reduce it substantially thereafter. A net zero CO_2 emissions goal would be easier to achieve than the net zero GHG emissions goal, which requires substantially negative CO_2 emissions, a point of recent concern. However, achieving net zero CO_2 emissions would still require rapid decarbonization, and separate limits on non-CO_2 emissions may be needed as well. If overshoot of the temperature goal occurred, as seems likely in the case of the 1.5 °C target, further action to create negative CO_2 emissions would be necessary to lower temperatures.").

[417] Arctic Council Secretariat (2017) EXPERT GROUP ON BLACK CARBON AND METHANE: SUMMARY OF PROGRESS AND RECOMMENDATIONS 2017, 2 ("To slow the pace of warming over the next two to three decades, both globally and in the Arctic, countries must reduce emissions of powerful short-lived climate pollutants (SLCPs) such as black carbon and methane as an essential complement to reductions of carbon dioxide and other long-lived greenhouse gas emissions. In fact, global action on carbon dioxide and other long-lived greenhouse gases together with SLCPs offers the only path to achieve the internationally agreed goal, as set forth in the Paris Agreement adopted by the Parties to the United Nations Framework Convention on Climate Change (UNFCCC), to limit warming to "well below" 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 degrees Celsius.").

[418] Arctic Monitoring and Assessment Programme (AMAP) (2017) SNOW, WATER, ICE, AND PERMAFROST IN THE ARCTIC: SUMMARY FOR POLICYMAKERS, 18 ("Stabilizing Arctic warming and its associated impacts will require substantial near-term cuts in net global greenhouse gas emissions. Full implementation of the Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC) will cause Arctic temperatures to stabilize—at a higher level than today—in the latter half of this century. This will require much larger cuts in global greenhouse gas emissions than those planned under current nationally determined contributions to the fulfillment of the UNFCCC.").

[419] UNEP & WMO (2011) INTEGRATED ASSESSMENT OF BLACK CARBON AND TROPOSPHERIC OZONE, 182 ("Implemented in full, the measures would be able to reduce the rate and total magnitude of global and regional warming by about half over the next 25 years relative to the reference scenario (see Figures 5.5a and 5.5d).").

[420] UNEP & WMO (2011) INTEGRATED ASSESSMENT OF BLACK CARBON AND TROPOSPHERIC OZONE, 262 ("Large impacts of the measures examined here were also seen for the Arctic despite the minimal amount of emissions currently taking place there. This occurs due to the high sensitivity of the Arctic both to pollutants that are transported there from remote sources and to radiative forcing that takes place in areas of the northern hemisphere outside the Arctic. The 16 measures examined here, including the measures on pellet stoves and coal briquettes, reduce warming in the Arctic by 0.7 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, 183–185 ("The screening revealed that the top 14 measures realized nearly 90% of the maximum reduction in net GWP…. Seven measures target CH_4 emissions, covering coal mining, oil and gas production, long-distance gas transmission, municipal waste and landfills, wastewater, livestock manure, and rice paddies. The others target emissions from incomplete combustion and include technical measures…, covering diesel vehicles, clean-burning biomass stoves, brick kilns, and coke ovens, as well as primarily regulatory measures…, including banning agricultural waste burning, eliminating high-emitting vehicles, and providing modern cooking and heating. We refer to these seven as "BC measures," although in practice, we consider all co-emitted species. …The global mean response to the CH_4 plus BC measures was –0.54 ± 0.05ºC in the climate model. …Roughly half the forcing is relatively evenly distributed (from the CH_4 measures). The other half is highly inhomogeneous, especially the strong BC forcing, which is greatest over bright desert and snow or ice surfaces. Those areas often exhibit the largest warming mitigation, making the regional temperature response to aerosols and ozone quite distinct from the more homogeneous response to well-mixed greenhouse gases…. BC albedo and direct forcings are large in the Himalayas, where there is an especially pronounced response in the Karakoram, and in the Arctic, where the measures reduce projected warming over the next three decades by approximately two thirds and where regional temperature response patterns correspond fairly closely to albedo forcing (for example, they are larger over the Canadian archipelago than the interior and larger over Russia than Scandinavia or the North Atlantic).").

[421] Xu Y. & Ramanathan V. (2017) *Well below 2 °C: Mitigation strategies for avoiding dangerous to catastrophic climate changes*, PROC. NAT'L. ACAD. SCI. 114(39):10315–10323, Table S1.

[422] 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 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 (32) is about 0.6 °C by 2050 and 1.2 °C by 2100 (SI Appendix, Fig. S5B and Table S1).").

[423] 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 ("While HFCs are not dependent on CO_2 mitigation, CO_2-dedicated mitigation measures can accomplish roughly 50% of the 0.6 °C mitigated warming by SLCPs by 2050 and 40% of the 1.2 °C mitigated warming by 2100.").

[424] Cumulative CO_2 emissions represent the total amount of CO_2 that can enter the atmosphere for a specified chance of remaining under a specific temperature, and in this case, 3.7 trillion tonnes of CO_2 yields a 50% chance of staying below 2 ºC of warming. *See generally* Meinshausen M., *et al.* (2009) *Greenhouse-gas emission targets for limiting global warming to 2 °C*, NATURE 458:1158–1162.

[425] 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 ("Earlier studies have identified that cumulative CO_2 emissions must be limited to less than 3.7 trillion tons (or 1 trillion tons of carbon) to have any chance of limiting the warming below 2 °C. These studies often focused on targeting the central value (50% probability) of the warming and less on the LPHI warming.").

[426] 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 ("It has taken society nearly 220 years (from 1750 to 1970) to emit the first trillion tons of CO_2 and only another 40 years (1970–2010) to emit the next trillion tons. The third trillion tons, under current emission trends, would be emitted by 2030 and the fourth trillion tons before 2050 (Box 1 and SI Appendix, Fig. S1A).").

[427] 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, 10318 ("Because of the inertia in the socioeconomic system, the emissions most likely cannot be brought to zero immediately. Even if a scalable renewable technology were invented today to zero out all of the CO_2 emissions, it would be likely to take between three and five decades to spread such technology to the whole world (28), assuming a globally binding policy for carbon neutrality had already been put into place. This delay is partly due to the locked-in infrastructure and the upfront capital cost of quickly replacing as opposed to distributing the cost over decades. This inference is also consistent with most scenario studies (29, 30) for carbon neutrality pathways. The opposite extreme of zeroing out CO_2 emissions by 2020 is a more gradual reduction to near-zero emissions by 2100. For this case, SI Appendix, Fig. S8B shows simulated CO_2 concentrations increase by ~20 ppm to peak levels by 2030 and stay flat post-2050 and CO_2-induced warming increases by another 0.6 °C (SI Appendix, Fig. S8C).").

[428] Erickson P., *et al.* (2015) *Assessing carbon lock-in*, ENVTL. RESEARCH LETTERS 10(084023):1–7, 1 ("[C]arbon lock-in refers to the dynamic whereby prior decisions relating to GHG-emitting technologies, infrastructure, practices, and their supporting networks constrain future paths, making it more challenging, even impossible, to subsequently pursue more optimal paths toward low-carbon objectives. Notably, the International Energy Agency has found that continued near-term (through 2020) investment in conventional technologies instead of low-carbon alternatives would increase investment costs four-fold in the longer term (through 2035). Others, including the Intergovernmental Panel on Climate Change and academic researchers, have similarly concluded that the greater carbon lock-in, the less the chance, and higher the cost of achieving ambitious climate goals, such as keeping warming below 2°C relative to pre-industrial levels. …By investing in assets prone to lock-in, planners and investors restrict future flexibility and increase the costs of achieving agreed climate protection goals.").

[429] Erickson P., *et al.* (2015) *Assessing carbon lock-in*, ENVTL. RESEARCH LETTERS 10(084023):1–7, 3 ("[C]onventional technologies might be retired early or 'unlocked' in the future, especially if the full costs of an alternative, low-carbon technology were to fall below the marginal (in this case, the ongoing operating) costs of the conventional technology, accounting for all climate policies (e.g., carbon pricing) and incentives.").

[430] Erickson P., *et al.* (2015) *Assessing carbon lock-in*, ENVTL. RESEARCH LETTERS 10(084023):1–7, 4 ("[G]lobally, coal-fired power plants are long-lived (averaging 45 years), and large numbers are expected over the next 15 years (over-committing 200 $GtCO_2$), creating further political and institutional entrenchment. Unlocking coal plants would, on average, require a carbon price of about USD 30 per tonne, lower than for most technologies, but still higher than carbon prices in most countries. This barrier to unlocking is driven primarily by coal power's low operating costs, which present stiff competition to newly-built renewables. Accordingly, coal plants present one of the greatest lock-in risks globally, a finding consistent with other recent modeling.").

[431] Jacobson M. Z., *et al.* (2015) *100% clean and renewable wind, water, and sunlight (WWS) all-sector energy roadmaps for the 50 United States*, ENERGY & ENVTL. SCIENCE 8:2093–2117, 2093 ("This study presents roadmaps for each of the 50 United States to convert their all-purpose energy systems (for electricity, transportation, heating/cooling, and industry) to ones powered entirely by wind, water, and sunlight (WWS). The plans contemplate 80–85% of existing energy replaced by 2030 and 100% replaced by 2050. Conversion would reduce each state's end-use power demand by a mean of ~39.3% with ~82.4% of this due to the efficiency of electrification and the rest due to end-use energy efficiency improvements. Year 2050 end-use U.S. all-purpose load would be met with ~30.9% onshore wind, ~19.1% offshore wind, ~30.7% utility-scale photovoltaics (PV), ~7.2% rooftop PV, ~7.3% concentrated solar power (CSP) with storage, ~1.25% geothermal power, ~0.37% wave power, ~0.14% tidal power, and ~3.01% hydroelectric power. Based on a parallel grid integration study, an additional 4.4% and 7.2% of power beyond that needed for annual loads would be supplied by CSP with storage and solar thermal for heat, respectively, for peaking and grid stability. Over all 50 states, converting would provide B3.9 million 40-year construction jobs and ~2.0 million 40-year operation jobs for the energy facilities alone, the sum of which would outweigh the ~3.9 million jobs lost in the conventional energy sector. Converting would also eliminate ~62000 (19000–115000) U.S. air pollution premature mortalities per year today and ~46000 (12000–104000) in 2050, avoiding ~$600 ($85–$2400) bil. per year (2013 dollars) in 2050, equivalent to ~3.6 (0.5–14.3) percent of the 2014 U.S. gross domestic product. Converting would further eliminate ~$3.3 (1.9–7.1) tril. per year in 2050 global warming costs to the world due to U.S. emissions. These plans will result in each person in the U.S. in 2050 saving ~$260 (190–320) per year in energy costs ($2013 dollars) and U.S. health and global climate costs per person decreasing by ~$1500 (210–6000) per year and ~$8300 (4700–17 600) per year, respectively.").

[432] International Energy Agency (IEA) (2018) GLOBAL ENERGY & CO_2 STATUS REPORT 2017, 9 ("Renewables saw the highest rate of growth of any energy source in 2017 and met around a quarter of global energy demand growth

last year. The power sector played the most important role in the growth of low-carbon energy, with renewables-based electricity generation increasing by 6.3% (380 TWh) in 2017. Renewables now account for 25% of global electricity generation. China and the United States together accounted for half of the increase in renewables-based electricity generation, followed by the European Union (8%), Japan and India (with 6% of growth each). The growth of wind power and solar PV in 2017 was unprecedented; wind power accounted for the largest share of overall renewables growth, at 36%, followed by solar PV (27%), hydropower (22%) and bioenergy (12%). China accounted for 40% of the combined growth in wind and solar PV, with new record capacity additions and a reduction in the rate of curtailment. Nearly 40% of the increase in hydropower was in the United States, while climatic conditions in the European Union reduced hydro output by nearly one-tenth. The European Union, China and Japan accounted for 82% of global bioenergy growth in power.").

[433] International Energy Agency (IEA) (2018) GLOBAL ENERGY & CO_2 STATUS REPORT 2017, 1 ("Renewables saw the highest growth rate of any energy source in 2017, meeting a quarter of global energy demand growth last year. China and the United States led this unprecedented growth, contributing around 50% of the increase in renewables-based electricity generation, followed by the European Union, India and Japan. Wind power accounted for 36% of the growth in renewables based power output.").

[434] International Energy Agency (IEA) (2018) GLOBAL ENERGY & CO_2 STATUS REPORT 2017, 1 ("Global energy demand increased by 2.1% in 2017, compared with 0.9% the previous year and 0.9% on average over the previous five years. More than 40% of the growth in 2017 was driven by China and India; 72% of the rise was met by fossil fuels, a quarter by renewables and the remainder by nuclear").

[435] International Energy Agency (IEA) (2018) GLOBAL ENERGY & CO_2 STATUS REPORT 2017, 1 ("Global energy-related CO_2 emissions grew by 1.4% in 2017, reaching a historic high of 32.5 gigatonnes (Gt), a resumption of growth after three years of global emissions remaining flat. The increase in CO_2 emissions, however, was not universal. While most major economies saw a rise, some others experienced declines, including the United States, United Kingdom, Mexico and Japan. The biggest decline drop came from the United States, mainly because of higher deployment of renewables.").

[436] International Energy Agency (IEA) (2018) GLOBAL ENERGY & CO_2 STATUS REPORT 2017, 3 ("Global energy-related CO_2 emissions rose by 1.4% in 2017, an increase of 460 million tonnes (Mt), and reached a historic high of 32.5 Gt. Last year's growth came after three years of flat emissions and contrasts with the sharp reduction needed to meet the goals of the Paris Agreement on climate change. The increase in carbon emissions, equivalent to the emissions of 170 million additional cars, was the result of robust global economic growth of 3.7%, lower fossil-fuel prices and weaker energy efficiency efforts. These three factors contributed to pushing up global energy demand by 2.1% in 2017.").

[437] International Energy Agency (IEA) (2018) GLOBAL ENERGY & CO_2 STATUS REPORT 2017, 1 ("World electricity demand increased by 3.1%, significantly higher than the overall increase in energy demand. Together, China and India accounted for 70% of this growth. Output from nuclear plants rose by 26 terawatt hours (TWh) in 2017, as a significant amount of new nuclear capacity saw its first full year of operation.").

[438] International Energy Agency (IEA) (2018) GLOBAL ENERGY & CO_2 STATUS REPORT 2017, 1 ("Improvements in global energy efficiency slowed down dramatically in 2017, because of weaker improvement in efficiency policy coverage and stringency as well as lower energy prices. Global energy intensity improved by only 1.7% in 2017, compared with an average of 2.3% over the last three years.").

[439] 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 third lever is the carbon extraction and sequestration (CES) lever, which will extract CO_2 from the source (e.g., the coal power plant) or from the air and sequester it. While the CN and SP levers can help mitigate the 50% probability warming targets, they are inadequate to mitigate the LPHI warming. Ultimately, we must thin the CO_2 greenhouse blanket by removing the CO_2 that is already in the atmosphere. Given the near-term risk of exceeding the dangerous to catastrophic thresholds, the timing for pulling these levers is a crucial issue. Ideally, these levers should be pulled immediately by 2020. We will now elaborate on three options to constrain the choices considered in earlier studies, starting with the least preferable option first."); *see also* Committee to Prevent Extreme Climate Change (2017) *Well Under 2 Degrees Celsius: Fast Action Policies to Protect People and the Planet from Extreme Climate Change*, 25–26.

[440] 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, 10315 ("Assess the low-probability (5%) high-impact (LPHI) warming outcomes in the absence of a climate mitigation policy after accounting for major uncertainties in: (a) future emission trajectories; (b) physical climate feedback involving water vapor, clouds, and snow/ice albedo; (c) carbon cycle feedback involving biogeochemistry; and (d) aerosol radiative forcing. We ensure

that the extreme outcomes projected in this study are consistent with published model parameters. The warming estimates in this study account for the well-known greenhouse gases (GHGs) and various aerosols.").

[441] 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, 10315 ("Because of uncertainties in emission scenarios, climate, and carbon cycle feedback, we interpret the Paris Agreement in terms of three climate risk categories and bring in considerations of low-probability (5%) high-impact (LPHI) warming in addition to the central (~50% probability) value. The current risk category of dangerous warming is extended to more categories, which are defined by us here as follows: >1.5 °C as dangerous; >3 °C as catastrophic; and >5 °C as unknown, implying beyond catastrophic, including existential threats. With unchecked emissions, the central warming can reach the dangerous level within three decades, with the LPHI warming becoming catastrophic by 2050. We outline a three-lever strategy to limit the central warming below the dangerous level and the LPHI below the catastrophic level, both in the near term (<2050) and in the long term (2100): the carbon neutral (CN) lever to achieve zero net emissions of CO_2, the super pollutant (SP) lever to mitigate short-lived climate pollutants, and the carbon extraction and sequestration (CES) lever to thin the atmospheric CO_2 blanket. Pulling on both CN and SP levers and bending the emissions curve by 2020 can keep the central warming below dangerous levels. To limit the LPHI warming below dangerous levels, the CES lever must be pulled as well to extract as much as 1 trillion tons of CO_2 before 2100 to both limit the preindustrial to 2100 cumulative net CO_2 emissions to 2.2 trillion tons and bend the warming curve to a cooling trend.").

[442] 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, 10322 ("This case involves pulling all three levers (CN, SP, and CES levers) with the CN2030 and the SLCP2020 options. This case is shown in Figs. 2 and 3 (green curves in both). The model simulations suggest that CES needs to be deployed by 2030 and to sequester 16 billion tons (Gt) of CO_2 per year (SI Appendix, Fig. S2C) for several decades into the late 21st century to limit the cumulative CO_2 emissions to 2.2 trillion tons (or 0.6 trillion tons of carbon). The CES of 16 Gt of CO_2 per year will extract one-third of the 3.2 trillion tons of CO_2 (CES1t) that would have been added by human activities since the industrial era. To get a perspective on the enormity of this extraction, the 2010 fossil fuel CO_2 emission is 32 Gt of CO_2 per year. This case meets all three criteria with a small exception. First, the option meets the criteria of limiting the long-term warming below the dangerous level (<50% probability of exceeding 1.5 °C) and below the catastrophic level (<5% probability of exceeding 3 °C). Next, the end-of-century temperature curve is trending downward, providing great relief for the expected sea level rise during centuries beyond 2100. The one exception is that this case does not limit the near-term warming below the dangerous level (with an "overshoot" at 2050)."); *see also* Hansen J., *et al.* (2017) *Young people's burden: requirement of negative CO_2 emissions*, EARTH SYSTEMS DYNAMICS 8:577–616, 590 ("Extraction of CO_2 from the air, also called negative emissions or carbon dioxide removal (CDR), is required if large, long-term excursion of global temperature above its Holocene range is to be averted, as shown above.").

[443] Hansen J., *et al.* (2017) *Young people's burden: requirement of negative CO_2 emissions*, EARTH SYSTEMS DYNAMICS 8:577–616, 577 ("Targets for limiting global warming thus, at minimum, should aim to avoid leaving global temperature at Eemian or higher levels for centuries. Such targets now require "negative emissions", i.e., extraction of CO_2 from the air. If phasedown of fossil fuel emissions begins soon, improved agricultural and forestry practices, including reforestation and steps to improve soil fertility and increase its carbon content, may provide much of the necessary CO_2 extraction."); *see also* Committee to Prevent Extreme Climate Change (2017) *Well Under 2 Degrees Celsius: Fast Action Policies to Protect People and the Planet from Extreme Climate Change*, 25–26.

[444] Molina M., *et al.* (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 ("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* Wallack J. S. & Ramanathan V. (2009) *The Other Climate Changers Why Black Carbon and Ozone Also Matter*, FOREIGN AFFAIRS 88(5):105–113, 113 ("At the current rate of global warming the earth's temperature stands to careen out of control. Now is the time to look carefully at all the

possible brakes that can be applied to slow climate change, hedge against near-term climate disasters, and buy time for technological innovations. Of the available strategies, focusing on reducing emissions of black carbon and ozone precursors is the low-hanging fruit: the costs are relatively low, the implementation is feasible, and the benefits would be numerous and immediate.").

445 Alexander L. V., *et al.* (2013) SUMMARY FOR POLICYMAKERS, *in* IPCC (2013) CLIMATE CHANGE 2013: THE PHYSICAL SCIENCE BASIS, Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 28 ("A large fraction of anthropogenic climate change resulting from CO_2 emissions is irreversible on a multi-century to millennial time scale, except in the case of a large net removal of CO_2 from the atmosphere over a sustained period. …Due to the long time scales of heat transfer from the ocean surface to depth, ocean warming will continue for centuries. Depending on the scenario, about 15 to 40% of emitted CO_2 will remain in the atmosphere longer than 1,000 years."); *see also* Matthews H. D. & Caldeira K. (2008) *Stabilizing climate requires near-zero emissions*, GEOPHYSICAL RESEARCH LETTERS 35(L04705):1–5, 1 ("[W]hile approximately half of the carbon emitted is removed by the natural carbon cycle within a century, a substantial fraction of anthropogenic CO_2 will persist in the atmosphere for several millennia.").

446 Hansen J., *et al.* (2007) *Climate change and trace gases*, PHIL. TRANS. R. SOC. 365:1925–1954, 1938 ("About one-quarter of fossil fuel CO_2 emissions will stay in the air "forever", i.e. more than 500 years…. Resulting climate changes would be … irreversible.").

447 Arctic Monitoring and Assessment Programme (AMAP) (2015) AMAP ASSESSMENT 2015: BLACK CARBON AND OZONE AS ARCTIC CLIMATE FORCERS, 97 ("Sulfur emission reductions implemented to improve air quality are enhancing climate warming. This is because sulfate (SO_4) aerosols formed from sulfur emissions scatter solar radiation and influence clouds, both of which cause climate cooling. Any reduction in sulfur emissions will therefore reduce the potential for cooling through SO_4 formation, and thus enhance warming. However, a mitigation strategy which also reduces the emissions of those SLCF components that actively warm the climate, especially methane (CH_4) and BC, could help offset warming induced by decreasing sulfur emissions, especially in the Arctic.").

448 UNEP & WMO (2011) INTEGRATED ASSESSMENT OF BLACK CARBON AND TROPOSPHERIC OZONE, 179, Box 5.1.

449 Shindell D., *et al.* (2012) *Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security*, SCIENCE 335(6065):183–189, Supporting Online Material, Table S1.

450 UNEP (2011) NEAR-TERM CLIMATE PROTECTION AND CLEAN AIR BENEFITS: ACTIONS FOR CONTROLLING SHORT-LIVED CLIMATE FORCERS, xi–xii. ("A package of 16 measures for reducing emissions of black carbon and methane has been identified that could provide substantial combined benefits for air quality and near-term climate protection. These measures can accomplish about 38 per cent reduction of global methane emissions and around 77 per cent of black carbon emissions, if implemented between now and 2030, relative to a 2030 'reference' emission scenario. The 'reference' scenario is based on a 'business-as-usual' energy demand projection and does not include any new legislation relevant to SLCF emissions beyond that already agreed.").

451 UNEP & WMO (2011) INTEGRATED ASSESSMENT OF BLACK CARBON AND TROPOSPHERIC OZONE, 262 ("Large impacts of the measures examined here were also seen for the Arctic despite the minimal amount of emissions currently taking place there. This occurs due to the high sensitivity of the Arctic both to pollutants that are transported there from remote sources and to radiative forcing that takes place in areas of the northern hemisphere outside the Arctic. The 16 measures examined here, including the measures on pellet stoves and coal briquettes, reduce warming in the Arctic by 0.7 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.")

452 Anenberg S. C., *et al.* (2012) *Global Air Quality and Health Co-benefits of Mitigating Near-Term Climate Change through Methane and Black Carbon Emission Controls*, ENVTL. HEALTH PERSPECTIVES 120:831–839, 838 ("We estimated the potential future air quality and health benefits resulting from implementing 14 specific methane and BC emission control measures selected for their near-term climate benefits. We estimate that these measures could reduce global population-weighted average surface $PM_{2.5}$ and ozone concentrations by 3.98–4.92 $\mu g/m^3$ (23.0–33.7%) and 4.71–11.0 ppb (6.5–17.0%), respectively, and avoid 0.6–4.4 and 0.04–0.52 million annual premature deaths globally in 2030. More than 80% of the health benefits of these measures are estimated to occur in Asia. Based on our estimates, avoided deaths would represent 1–8% of cardiopulmonary and lung cancer deaths among those ≥ 30 years of age and 1–7% of all deaths for all ages, assuming constant baseline mortality rates."); *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, 183 ("This strategy avoids 0.7 to 4.7 million annual premature deaths from outdoor air pollution and increases annual crop yields by 30 to 135 million metric tons due to ozone reductions in 2030 and beyond."); *and* UNEP & WMO (2011) INTEGRATED ASSESSMENT OF BLACK CARBON AND

TROPOSPHERIC OZONE, 173 ("The combined impact of the package of measures studied here would lead to a worldwide benefit in crop yields compared to the 2030 reference scenario from a 1.3 per cent (+1.5 per cent, –1.2 per cent) yield increase for rice to a 3.2 per cent (+1.6 per cent, –1.1 per cent) increase for soybeans. These benefits arise from the reductions in tropospheric O_3 resulting from application of the measures. The largest benefits emerge in the two Asian regions studied. The total global production gains of all crops range between 30 and 140 million tonnes (model mean: 52 million tonnes). The economic gains for all four crops in all regions range between US$4 billion and US$33 billion, of which US$2–28 billion are in Asia.").

[453] UNEP (2011) NEAR-TERM CLIMATE PROTECTION AND CLEAN AIR BENEFITS: ACTIONS FOR CONTROLLING SHORT-LIVED CLIMATE FORCERS, x ("The health benefits from implementing black carbon mitigation measures would be realized immediately and almost entirely in the regions that reduce their emissions. Regions taking action on black carbon would also benefit significantly from reduced regional warming, reduced disruption of regional weather patterns, as well as a substantial reduction in crop-yield losses.").

[454] Arctic Council Secretariat (2017) EXPERT GROUP ON BLACK CARBON AND METHANE: SUMMARY OF PROGRESS AND RECOMMENDATIONS 2017.

[455] Arctic Council Secretariat (2017) EXPERT GROUP ON BLACK CARBON AND METHANE: SUMMARY OF PROGRESS AND RECOMMENDATIONS 2017, 5 ("Reduce emissions from new diesel vehicles and engines by adopting world-class Particulate Matter (PM) exhaust emission standards that require the use of best available control technologies (such as diesel particulate filters (DPF)) or use of alternative fuels. Emissions from legacy diesel vehicles and engines could be reduced by adopting targeted grants, fiscal measures, and/or regulations that support or require the early upgrading or replacing of legacy equipment. In addition, because high-sulphur diesel fuel disrupts operation of advanced emission control technologies, it is essential to ensure the availability and use of clean fuels through policies and programs including mandatory fuel quality standards for on- and non-road applications, with regional requirements and fiscal policy incentives where needed, as well as robust compliance programs. Engagement with other countries to provide technical cooperation to reduce emissions from diesel powered mobile sources is particularly needed. Countries can complement policies and programs targeting diesel vehicles and engines by adopting incentives that encourage a shift from diesel passenger vehicles to lower emitting vehicle technologies, modes of transportation, and alternate fuels, as well as implementing transportation efficiency measures.").

[456] Arctic Council Secretariat (2017) EXPERT GROUP ON BLACK CARBON AND METHANE: SUMMARY OF PROGRESS AND RECOMMENDATIONS 2017, 6 ("Reduce methane emissions from the oil/gas sector by developing and promptly implementing national oil/gas methane emission reduction strategies, including steps to improve emissions data. Encourage firms headquartered or operating within their borders to join multilateral fora (e.g., Climate and Clean Air Oil and Gas Methane Partnership) and domestic programs (e.g. Natural Gas STAR) to promote voluntary action and enhance methane emissions data availability.").

[457] Arctic Council Secretariat (2017) EXPERT GROUP ON BLACK CARBON AND METHANE: SUMMARY OF PROGRESS AND RECOMMENDATIONS 2017, 7 ("Reduce black carbon emissions from new and legacy residential-scale biomass combustion appliances, while also adopting energy efficiency measures for homes that are primarily heated using biomass. Developing and deploying effective education and awareness campaigns to reduce operator error is essential to reducing emissions from all in-use heating appliances. Develop and, where possible, adopt a standardized testing protocol for black carbon emissions to ensure that new biomass combustion appliances are cleaner and more efficient. This can support the development of voluntary or regulatory performance and energy efficiency standards and incentive programs. Work with appliance manufacturers to ensure lower emitting and more efficient appliances are widely available and affordable. Incentivize replacement of older biomass combustion appliances with cleaner and more efficient alternatives to reduce emissions from *legacy* heating appliances.").

[458] Arctic Council Secretariat (2017) EXPERT GROUP ON BLACK CARBON AND METHANE: SUMMARY OF PROGRESS AND RECOMMENDATIONS 2017, 8 ("Avoid methane emissions from solid waste through policies that encourage waste minimization (especially food waste), diversion and alternative treatment, and ban or incentivize the banning of landfilling organic waste. Adopt policies or regulations that incentivize or require landfill gas capture and control, as well as require or incentivize utilization of methane generated from landfills in order to drive down emissions from existing, new, modified or reconstructed landfills.").

[459] Arctic Council Secretariat (2017) EXPERT GROUP ON BLACK CARBON AND METHANE: SUMMARY OF PROGRESS AND RECOMMENDATIONS 2017, 12 ("Arctic States must demonstrate leadership at home by continuing to drive down their emissions. It is important to note, however, that black carbon and methane emissions from non-Arctic States are a significant contributor to Arctic warming. Therefore, the Expert Group invites Arctic Council Observer States, and other States whose emissions impact the Arctic region, to consider adopting these recommendations or related measures keeping in mind the urgency of the long-term temperature goal set forth in the Paris Agreement. The

Expert Group also encourages Arctic States to consider areas where domestic mitigation could be complemented by international cooperation with non-Arctic States, especially for major source categories that strongly impact the Arctic. These contributions through international cooperation should be systematically evaluated and included in future biennial national reports as called for under the Framework."); *see also* Arctic Monitoring and Assessment Programme (AMAP) (2015) AMAP ASSESSMENT 2015: METHANE AS AN ARCTIC CLIMATE FORCER, 49–50 ("The largest abatement potentials are found from reduced venting of associated gas released during oil production; reduced leakage from natural gas production, transmission and distribution; source separation and treatment of biodegradable waste to replace landfill disposal; and control of coal mine methane emissions through extended pre-mining degasification and installation of ventilation air oxidizers during mining. The technical abatement potential in the agricultural sector is found to be relatively limited. Options include changes in management practices to control methane emissions from continuously flooded rice fields and some limited reduction potentials from control of methane from enteric fermentation through changes in animal diets for ruminant livestock and anaerobic digestion of manure (Hristov et al. 2013). More extensive emission reductions in the agricultural sector would involve non-technical options, such as broader structural changes in production and consumption systems (see Box 5.2).").

460 Arctic Council Secretariat (2017) EXPERT GROUP ON BLACK CARBON AND METHANE: SUMMARY OF PROGRESS AND RECOMMENDATIONS 2017, 11 ("For black carbon, emissions from within Arctic States account for about one third of black carbon's warming effects in the Arctic, despite accounting for only 10 percent of global black carbon emissions. This is because black carbon from proximate sources is readily transported to the Arctic, is found in the lower Arctic atmosphere and can fall onto Arctic ice or snow. These processes lead to strong surface warming through direct atmospheric effects and by enhanced melting of ice and snow (i.e. ice-albedo feedbacks). It should be noted that even black carbon from non-proximate sources contributes to overall warming of the planet, including the Arctic.").

461 Arctic Council Secretariat (2017) EXPERT GROUP ON BLACK CARBON AND METHANE: SUMMARY OF PROGRESS AND RECOMMENDATIONS 2017, 11 ("For methane, Arctic States account for roughly one fifth of global anthropogenic emissions. While methane emitted anywhere in the world warms the Arctic, Arctic States have the largest technical abatement potential of any major world region and could achieve one fourth of global methane emission reductions primarily by: reducing methane leakage, venting and flaring from the oil and natural gas sector; preventing the landfilling of biodegradable waste; and improving coal mining practices.").

462 Arctic Monitoring and Assessment Programme (AMAP) (2015) AMAP ASSESSMENT 2015: METHANE AS AN ARCTIC CLIMATE FORCER, 39 ("Since methane is well mixed in the global atmosphere, it is important to assess the potential to reduce warming in the Arctic region through reductions in methane emissions globally as well as by the Arctic nations themselves. It is estimated that more than half of the anthropogenic methane emissions from Arctic nations come from the fossil fuel sector and that these contribute about a third of global methane emissions from fossil fuel sources. Managing future methane emissions from these activities is therefore of particular importance in Arctic nations. Methane emissions from fossil fuel sources have thus received special attention in this chapter.").

463 Arctic Monitoring and Assessment Programme (AMAP) (2015) AMAP ASSESSMENT 2015: METHANE AS AN ARCTIC CLIMATE FORCER, 41 ("All inventories cover the major methane emission sources: fossil fuel production, transmission and distribution; livestock (enteric fermentation and manure management); rice cultivation; solid waste and wastewater."). *See also* AMAP) (2015) AMAP ASSESSMENT 2015: METHANE AS AN ARCTIC CLIMATE FORCER, 42 (Figure 5.1).

464 Arctic Monitoring and Assessment Programme (AMAP) (2015) AMAP ASSESSMENT 2015: BLACK CARBON AND OZONE AS ARCTIC CLIMATE FORCERS, 12 ("Methane oxidation leads to the production of O_3 in the presence of sufficient NO_X and it has been estimated that anthropogenic CH_4 emissions may be responsible for about half of pre-industrial to present-day O_3 radiative forcing (Stevenson et al. 2013) as well as about half of the projected future surface O_3 increases (Prather et al. 2003). CH_4 oxidation contributes to background O_3 away from emission regions, such as in the Arctic and may be responsible for a significant proportion of the positive trends in O_3 concentrations observed in the northern hemisphere over the past decades (Parrish et al. 2012b). Fiore et al. (2009) estimated that a 20% reduction in anthropogenic CH_4 emissions would lead to about a 1 ppbv decrease in tropospheric O_3, comparable to combined reductions in NO_X, CO, and VOC emissions. However, although reduced NO_X emissions lead to decreased O_3 levels, they also lead to decreased OH concentrations and therefore increased CH_4, thus offsetting the climate benefit of decreased O_3 (West et al. 2007).").

465 Bond T. C., *et al.* (2013) *Bounding the role of black carbon in the climate system: A scientific assessment*, J. GEOPHYSICAL RESEARCH–ATMOSPHERES 118(11):5380–5552, 5388 ("Mitigation of diesel-engine sources appears to offer the most confidence in reducing near-term climate forcing. Mitigating emissions from residential solid fuels

also may yield a reduction in net positive forcing. The net effect of other sources, such as small industrial coal boilers and ships, depends on the sulfur content, and net climate benefits are possible by mitigating some individual source types.").

466 Bahadur R., *et al.* (2011) *Impact of California's air pollution laws on black carbon and their implications for direct radiative forcing*, ATMOSPHERIC ENV'T. 45(5):1162–1167, 1162 ("Annual average BC concentrations in California have decreased by about 50% from 0.46 μg m^{-3} in 1989 to 0.24 μ gm^{-3} in 2008 compared to the corresponding reductions in diesel BC emissions (also about 50%) from a peak of 0.013 Tg Yr^{-1} in 1990 to 0.006 Tg Yr^{-1} by 2008. We attribute the observed negative trends to the reduction in vehicular emissions due to stringent statewide regulations. Our conclusion that the reduction in diesel emissions is a primary cause of the observed BC reduction is also substantiated by a significant decrease in the ratio of BC to non-BC aerosols.").

467 Arctic Council Secretariat (2017) EXPERT GROUP ON BLACK CARBON AND METHANE: SUMMARY OF PROGRESS AND RECOMMENDATIONS 2017, 17 ("According to the 2013 inventories, on-road and non-road mobile sources (excluding international shipping and international aviation) represent 61 percent of black carbon emissions for Arctic States. All Arctic States, and all Arctic Council Observer States participating in the Expert Group, have implemented some combination of the following approaches to reduce black carbon emissions from diesel mobile sources: Mandatory *exhaust emission standards* for new vehicles and engines; Targeted policies and programs for *legacy vehicles and engines* (i.e., those still in use that were manufactured before current standards took effect); Mandatory standards to *reduce sulphur levels in fuels* for use in vehicles and engines, which enable the use of best available control technologies, such as diesel particulate filters (DPFs); and Shifts to reduce emissions overall, such as to alternate fuels or transportation modes.").

468 Sand M., *et al.* (2016) *Response of Arctic temperature to changes in emissions of short-lived climate forcers*, NATURE CLIMATE CHANGE 6:286–289, 287 ("In terms of volume, the largest contribution to the reduction in Arctic warming comes from an improved domestic heating and cooking sector in Asia and in the rest of the world. Such measures see large cuts in warming from BC, although those benefits are offset 25–40% by reductions in the cooling effect of co-emitted OC.").

469 Lam N. L., *et al.* (2012) *Household Light Makes Global Heat: High Black Carbon Emissions From Kerosene Wick Lamps*, ENVTL. SCIENCE & TECHNOLOGY 46(24):13531–13538, 13531 ("Kerosene-fueled wick lamps used in millions of developing-country households are a significant but overlooked source of black carbon (BC) emissions…. Kerosene lamps have affordable alternatives that pose few clear adoption barriers and would provide immediate benefit to user welfare…. No other major BC source has such readily available alternatives, definitive climate forcing effects, and cobenefits. Replacement of kerosene-fueled wick lamps deserves strong consideration for programs that target short-lived climate forcers.").

470 Ramanathan V. & Carmichael G. (2008) *Global and regional climate changes due to black carbon*, NATURE GEOSCIENCE 1:221–227, 221 ("Black carbon (BC) is an important part of the combustion product commonly referred to as soot. BC in indoor environments is largely due to cooking with biofuels such as wood, dung and crop residue. Outdoors, it is due to fossil fuel combustion (diesel and coal), open biomass burning (associated with deforestation and crop residue burning), and cooking with biofuels. Soot aerosols absorb and scatter solar radiation. BC refers to the absorbing components of soot, often defined using elemental carbon and some condensed organics. Recent findings suggest other secondary organics also contribute to strong absorption in the ultraviolet region of the spectrum, components that were presumably ignored in the original definition of BC.").

471 Molina M., *et al.* (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):20,616–20,621, 20,619 ("BC can be reduced by approximately 50% with full application of existing technologies by 2030…. Strategies to reduce BC could borrow existing management and institutions at the international and regional levels, including existing treaty systems regulating shipping and regional air quality."); *see also* UNEP (2011) NEAR-TERM CLIMATE PROTECTION AND CLEAN AIR BENEFITS: ACTIONS FOR CONTROLLING SHORT-LIVED CLIMATE FORCERS, x ("National efforts to reduce SLCFs can build upon existing institutions, policy and regulatory frameworks related to air quality management, and, where applicable, climate change. …Regional air pollution agreements, organizations and initiatives may be effective mechanisms to build awareness, promote the implementation of SLCF mitigation measures, share good practices and enhance capacity. …Global actions can help enable and encourage national and regional initiatives and support the widespread implementation of SLCF measures. A coordinated approach to combating SLCFs can build on existing institutional arrangements, ensure adequate financial support, enhance capacity and provide technical assistance at the national level."); *and* Shindell D., *et al.* (2012) *Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security*, SCIENCE 335(6065):183–

189, 188 ("Many other policy alternatives exist to implement the CH_4 and BC measures, including enhancement of current air quality regulations.").

[472] UNEP (2011) NEAR-TERM CLIMATE PROTECTION AND CLEAN AIR BENEFITS: ACTIONS FOR CONTROLLING SHORT-LIVED CLIMATE FORCERS, x ("About 50 per cent of both methane and black carbon emission reductions can be achieved through measures that result in net cost savings (as a global average) over their technical lifetime. The savings occur when initial investments are offset by subsequent cost savings from, for example, reduced fuel use or utilization of recovered methane. A further third of the total methane emission reduction could be addressed at relatively moderate costs.").

[473] Shindell D., *et al.* (2012) *Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security*, SCIENCE 335(6065):183–189, 183 ("Benefits of methane emissions reductions are valued at $700 to $5000 per metric ton, which is well above typical marginal abatement costs (less than $250).").

[474] 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 ("CO_2-dedicated measures: Technology measures to curb CO_2 emissions such as switching to renewables will also mitigate some of the emissions of SLCPs: methane (22% of methane emissions are due to production and consumption of fossil fuels), BC emitted by diesel vehicles, and emissions of ozone precursors such as carbon monoxide and NO_X (nitrogen oxides) by fossil fuel consumption (32, 33).").

[475] 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 ("The mitigation of the coemitted SLCPs and cooling aerosols by CO_2-dedicated measures requires special consideration. SLCP emissions are not entirely independent of CO_2 emissions, and emission rates of SLCPs can decrease due to CO_2 mitigation, and likewise CO_2 emissions can decrease due to mitigation of SLCPs. The role of coemitted SLCPs that are dependent on CO_2 is estimated in SI Appendix, Fig. S5. A fraction of CH_4 (about 70%) and BC (about 30%) emissions can be mitigated through CO_2-dedicated measures.").

[476] Shindell D., *et al.* (2012) *Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security*, SCIENCE 335(6065):183–189, 186 ("[T]he bulk of the BC measures could probably be implemented with costs substantially less than the benefits given the large valuation of the health impacts.").

[477] UNEP (2011) NEAR-TERM CLIMATE PROTECTION AND CLEAN AIR BENEFITS: ACTIONS FOR CONTROLLING SHORT-LIVED CLIMATE FORCERS, 13–16 ("[A]bout half of the temperature reduction would emerge from Group 1 measures [low cost methane and black carbon measures], which result in net cost savings to society over their full technical lifetime. However, the required up-front investments over an assumed 20 years implementation period do constitute a considerable barrier to implementation. Prevailing short-term profit expectations of private investors make these measures less attractive to the market. …For all Group 1 measures, targeted interventions or appropriate financing mechanisms could help to overcome implementation barriers. In comparison, measures of Group 2, which could potentially be competitive on a carbon market, require much lower up-front investments, especially for methane recovery in coal mines. …Some of the more costly measures for controlling SLCFs are often/usually implemented for other development related objectives.").

[478] Arctic Council Secretariat (2017) EXPERT GROUP ON BLACK CARBON AND METHANE: SUMMARY OF PROGRESS AND RECOMMENDATIONS 2017, 19 ("Encouraging shifts to less-polluting modes of transit and taxing pollution are effective in reducing black carbon emissions. Many Arctic and Observer States have also implemented sustainable transportation initiatives that encourage a shift from diesel passenger vehicles to more environmentally friendly vehicles or transport modes with lower emissions. For example, Germany is awarding EUR4,000 per electric vehicle purchased, and EUR3,000 per plug-in hybrid vehicle purchased. Incentives help spur voluntary adoption of emission control measures in the shipping industry. Some Arctic States are providing incentives to motivate industry adoption of emission-reduction strategies and technologies. These include engine rebuilds and the use of advanced after-treatment technologies including installation of DPF and deployment of marine shore power technology at ports so that ships do not need to run marine diesel generators to power onboard systems while pier-side. In Europe, many ports are required to be equipped with shore-side electricity supply for inland waterway vessels and sea-going ships by December 31, 2025. In Germany, the "Blue Angel" ecolabel, existing since 1978, contains a sub-category certifying environmentally-friendly ship design and operation, incentivizing the use of clean fuels and environmentally conscious ship management.").

[479] Arctic Council Secretariat (2017) EXPERT GROUP ON BLACK CARBON AND METHANE: SUMMARY OF PROGRESS AND RECOMMENDATIONS 2017, 18 ("Mandatory emissions standards for new diesel vehicles and engines that in practice require a combination of DPFs and low-sulphur fuel have been highly effective, net beneficial, and widely adopted across most participating countries.").

[480] Arctic Council Secretariat (2017) EXPERT GROUP ON BLACK CARBON AND METHANE: SUMMARY OF PROGRESS AND RECOMMENDATIONS 2017, 18 ("Implementation of standards that require a fuel sulphur level of 15 parts per million or below is an essential pre-requisite to stringent emissions standards, since these enable the use and effective operation of vehicle and engine exhaust after-treatment systems, such as DPFs that can nearly eliminate black carbon emissions. While low sulphur fuel is widely available in many Arctic States, there are a number of barriers that can impede its availability in some countries. These barriers include the cost of upgrading refineries, and of keeping fuels low sulphur throughout the fuel distribution chain (i.e. avoiding contamination with higher sulphur fuels).").

[481] UNEP & WMO (2011) INTEGRATED ASSESSMENT OF BLACK CARBON AND TROPOSPHERIC OZONE, 171–174.

[482] Arctic Council Secretariat (2017) EXPERT GROUP ON BLACK CARBON AND METHANE: SUMMARY OF PROGRESS AND RECOMMENDATIONS 2017, 3 ("Black carbon and methane emissions also contribute directly to air pollution that harms human health, in addition to the health impacts due to climate change itself. Black carbon does so directly as a component of particulate matter (PM), while methane does so by contributing to formation of ground-level ozone, which also significantly impairs agricultural productivity. Therefore, actions that reduce emissions of black carbon and methane today also achieve substantial local and global non-climate benefits.").

[483] Arctic Monitoring and Assessment Programme (AMAP) (2017) ADAPTATION ACTIONS FOR A CHANGING ARCTIC: PERSPECTIVES FROM THE BARENTS AREA, 72 ("The adverse effects of fine atmospheric particulates on human health have been well documented, with no evidence of a safe level of exposure or threshold below which no effects occur (WHO, 2013).").

[484] World Health Organization (WHO) (2014) *Burden of disease from the joint effects of Household and Ambient Air Pollution for 2012*, Summary of Results ("Globally, 7 million deaths were attributable to the joint effects of household (HAP) and ambient air pollution (AAP) in 2012. The Western Pacific and South East Asian regions bear most of the burden with 2.8 and 2.3 million deaths, respectively. Almost 680'000 deaths occur in Africa, about 400'000 in the Eastern Mediterranean region, 287'000 in Europe and 131'000 in the Americas. The remaining deaths occur in high-income countries of Europe (295'000), Americas (96'000), Western Pacific (68'000), and Eastern Mediterranean (14'000).").

[485] World Health Organization (WHO) (2014) *Burden of disease from Ambient Air Pollution for 2012*, Summary of Results ("Globally, 3.7 million deaths were attributable to ambient air pollution (AAP) in 2012. About 88% of these deaths occur in low- and middle-income (LMI) countries, which represent 82% of the world population. The Western Pacific and South East Asian regions bear most of the burden with 1.67 million and 936'000 deaths, respectively. About 236'000 deaths occur in the Eastern Mediterranean region, 200'000 in Europe, 176'000 in Africa, and 58'000 in the Americas. The remaining deaths occur in high-income countries of Europe (280'000), Americas (94'000), Western Pacific (67'000), and Eastern Mediterranean (14'000).").

[486] World Health Organization (WHO) (2014) *Burden of disease from Household Air Pollution for 2012*, Summary of Results ("Globally, 4.3 million deaths were attributable to household air pollution (HAP) in 2012, almost all in low and middle income (LMI) countries. The South East Asian and Western Pacific regions bear most of the burden with 1.69 and 1.62 million deaths, respectively. Almost 600'000 deaths occur in Africa, 200'000 in the Eastern Mediterranean region, 99'000 in Europe and 81'000 in the Americas. The remaining 19'000 deaths occur in high income countries.").

[487] OECD (2012) *OECD Environmental Outlook to 2050: The Consequences of Inaction*, 1 ("Air pollution is set to become the world's top environmental cause of premature mortality, overtaking dirty water and lack of sanitation. Air pollution concentrations in some cities, particularly in Asia, already far exceed World Health Organization safe levels, and they are projected to deteriorate further to 2050…. The number of premature deaths from exposure to particulate matter … is projected to more than double worldwide, from just over 1 million today to nearly 3.6 million per year in 2050, with most deaths occurring in China and India…. The absolute number of premature deaths from exposure to ground-level ozone is to more than double worldwide (from 385 000 to nearly 800 000) between 2010 and 2050. Most of these deaths are expected to occur in Asia, where the ground-level ozone concentrations as well as the size of the exposed population are likely to be highest.").

[488] Landrigan P. J., *et al.* (2018) *The Lancet Commission on pollution and health*, LANCET 391(10119):462–512, 463 ("Pollution mitigation and prevention can yield large net gains both for human health and the economy. Thus, air quality improvements in the high-income countries have not only reduced deaths from cardiovascular and respiratory disease but have also yielded substantial economic gains. In the USA, an estimated US$30 in benefits (range, $4–88) has been returned to the economy for every dollar invested in air pollution control since 1970, which is an aggregate benefit of $1.5 trillion against an investment of $65 billion.").

[489] Landrigan P. J., *et al.* (2018) *The Lancet Commission on pollution and health*, LANCET 391(10119):462–512, 466 ("Contrary to the oft-repeated claim that pollution control stifles economic growth, pollution prevention has, in fact, been shown repeatedly to be highly cost-effective. In the USA, for example, concentrations of six common air pollutants have been reduced by about 70% since passage of the Clean Air Act in 1970 and, in the same time period, GDP has increased by nearly 250% (figure 1). Every dollar invested in control of ambient air pollution in the USA not only improves health, but also is estimated to yield US$30 in economic benefits (95% CI $4–88).").

[490] Hu A., *et al.* (2013) *Mitigation of short-lived climate pollutants slows sea-level rise*, NATURE CLIMATE CHANGE 3:730–734, 732 ("In comparison with the BAU case, mitigation of SLCPs can reduce the SLR_{full} rate by about 18% (from 1.1 cm yr^{-1} to about 0.9 cm yr^{-1}), and the SLR_{ther} rate by about 48% (from 0.29 cm yr^{-1} to 0.15 cm yr^{-1}), with negligible effect from CO_2 reduction before 2050. By 2100, however, CO_2 mitigation can reduce the SLR_{full} rate by about 24% (from 2.1 to 1.6 cm yr^{-1}), and the SLR_{ther} rate by about 25% (from 0.4 to 0.3 cm yr^{-1}). The SLCP mitigation would contribute about 24% of the SLR_{full} rate reduction, and 54% of the SLRther rate at 2100. With mitigation of both SLCPs and CO_2, the projected SLR rate is reduced by close to 50% for SLR_{full}, and 67% for SLR_{ther} by 2100.").

[491] Hu A., *et al.* (2013) *Mitigation of short-lived climate pollutants slows sea-level rise*, NATURE CLIMATE CHANGE 3:730–734, 732 ("With both the CO_2 and the SLCP mitigation, the projected SLR_{full} (from 2005 to 2100) is reduced by 31% from the BAU case; about 9% of that 31% is due to CO_2 mitigation and the balance of 22% is due to SLCPs.").

[492] Hu A., *et al.* (2013) *Mitigation of short-lived climate pollutants slows sea-level rise*, NATURE CLIMATE CHANGE 3:730–734, 732 ("The individual contributions from the various SLCPs are shown in Fig. 2c. The methane mitigation has the largest effect in mitigating SLR with CO_2 next, followed by black carbon and HFCs. Most (~53%) of the methane effects on temperature and SLR, shown in Fig. 2c, are due to the direct greenhouse effect. As methane is also involved in complex photochemical destruction and chemical oxidation processes in the atmosphere, about 27% of its effects are due to indirectly reducing tropospheric ozone, stratospheric water vapour and CO_2. The balance of 20% is due to CO mitigation actions reducing production of tropospheric ozone and methane.").

[493] Hu A., *et al.* (2013) *Mitigation of short-lived climate pollutants slows sea-level rise*, NATURE CLIMATE CHANGE 3:730–734, 730 ("Our results show that SLCP mitigation can have significant effects on SLR. It can decrease the SLR rate by 24–50% and reduce the cumulative SLR by 22–42% by 2100. If the SLCP mitigation is delayed by 25 years, the warming from pre-industrial temperature exceeds 2 ºC by 2050 and the impact of mitigation actions on SLR is reduced by about a third.").

[494] Bouttes N., *et al.* (2013) *The Reversibility of Sea Level Rise*, J. CLIMATE 26:2502–2513, 2502 ("Whereas surface temperature depends on cumulative CO_2 emissions, sea level rise due to thermal expansion depends on the time profile of emissions. Sea level rise is smaller for later emissions, implying that targets to limit sea level rise would need to refer to the rate of emissions, not only to the time integral.").

[495] Arctic Monitoring and Assessment Programme (AMAP) (2017) ADAPTATION ACTIONS FOR A CHANGING ARCTIC: PERSPECTIVES FROM THE BARENTS AREA, 72 ("Highly reflective surfaces, such as snow and ice in the Arctic increase light absorption by BC particles in the atmosphere. BC also absorbs light after deposition onto (and then into) snow and ice, where it accelerates the melt process (Pedersen et al., 2015). BC has made an important contribution to the observed rise in Arctic surface temperature through the 20th century (although carbon dioxide is still the major factor driving the rise in Arctic temperature) (Quinn et al., 2008; Koch et al., 2011; AMAP, 2015a). It may be technically possible to reduce global anthropogenic BC emissions by up to 75% by 2030 (Shindell et al., 2012; AMAP, 2015a; Stohl et al., 2015). As well as helping to slow warming, BC emission reductions would also have significant health benefits (Anenberg et al., 2012; Shindell et al., 2012)."); *see also* International Energy Agency (IEA) (2016) WORLD ENERGY OUTLOOK SPECIAL REPORT: ENERGY AND AIR POLLUTION, 115 ("Two areas of clear cross-benefit (for air quality and climate change) are actions to reduce emissions of black carbon, a major component of PM, and of methane (Box 3.4). Black carbon – emitted due to incomplete combustion, particularly from household biomass stoves and diesel vehicles – affects the climate in multiple ways. It absorbs incoming sunlight, leading to warming in the atmosphere, settles on the ground accelerating the melting of Arctic and alpine ice and, along with other pollutants that form aerosols, it affects the formation of clouds, so having a knock-on influence on increased warming."); *and* World Bank & International Cryosphere Climate Initiative (2013) ON THIN ICE: HOW CUTTING POLLUTION CAN SLOW WARMING AND SAVE LIVES, 2 ("Climate benefits for cryosphere regions from black carbon reductions carry less uncertainty than they would in other parts of the globe and are sometimes very large. This is because emissions from sources that emit black carbon—even with other pollutants—almost always lead to warming over reflective ice and snow.").

[496] Shindell D. & Faluvegi G. (2009) *Climate response to regional radiative forcing during the twentieth century*, NATURE GEOSCIENCE 2:294–300, 298 ("[T]he net impact on 1890–2007 Arctic surface temperatures has been –0.6ºC from tropical aerosols, +0.4ºC from mid-latitude aerosols and +0.5ºC from Arctic aerosols. Hence, long-term aerosol-induced Arctic climate change is quite sensitive to forcing at lower latitudes, which is not subject to these uncertainties. During 1976–2007, however, large changes in mid-latitude emissions have increased the importance of local Arctic forcing, with estimated surface temperature changes of –0.3ºC from tropical aerosols, +0.6ºC from mid-latitude aerosols and +0.8ºC from Arctic aerosols during this time. Our calculations suggest that black carbon and tropospheric ozone have contributed ~0.5–1.4 C and ~0.2–0.4ºC, respectively, to Arctic warming since 1890, making them attractive targets for Arctic warming mitigation. In addition, they respond quickly to emissions controls, and reductions have ancillary benefits including improved human and ecosystem health.").

[497] Sand M., *et al.* (2016) *Response of Arctic temperature to changes in emissions of short-lived climate forcers*, NATURE CLIMATE CHANGE 6:286–289, 286 ("We find that the largest Arctic warming source is from emissions within the Asian nations owing to the large absolute amount of emissions. However, the Arctic is most sensitive, per unit mass emitted, to SLCFs emissions from a small number of activities within the Arctic nations themselves. A stringent, but technically feasible mitigation scenario for SLCFs, phased in from 2015 to 2030, could cut warming by 0.2 (±0.17) K in 2050.").

[498] Arctic Council Secretariat (2017) EXPERT GROUP ON BLACK CARBON AND METHANE: SUMMARY OF PROGRESS AND RECOMMENDATIONS 2017, 2 ("In addition to its powerful atmospheric warming, black carbon that falls on snow and ice also accelerates the melting of these reflective surfaces and consequently global warming. Due to their proximity to the Arctic, Arctic States are uniquely positioned to slow Arctic warming caused by emissions of black carbon: despite generating just ten percent of global black carbon emissions, Arctic States are responsible for 30 percent of black carbon's warming effects in the Arctic."); *see also* Arctic Monitoring and Assessment Programme (AMAP) (2017) ADAPTATION ACTIONS FOR A CHANGING ARCTIC: PERSPECTIVES FROM THE BARENTS AREA, 72 ("Local emissions currently represent only a small fraction of the BC found in the Arctic, much of it having been transported into the Arctic via long-range transport from lower latitudes. However, higher latitude emissions are more likely to end up on the Arctic surface. In relative terms, emissions close to and within the Arctic region have a larger impact per unit of emission than those at more distant sites (AMAP 2015b). According to AMAP (2015a), the eight Arctic nations are responsible for about 30% of the Arctic warming due to BC. Thus emission reductions within the Arctic Council member countries could help reduce warming and lead to related health benefits, especially within the Arctic.").

[499] Arctic Monitoring and Assessment Programme (AMAP) (2017) ADAPTATION ACTIONS FOR A CHANGING ARCTIC: PERSPECTIVES FROM THE BARENTS AREA, 1 ("Changes in climate will have direct impacts on snow and ice, as well as on terrestrial, freshwater and marine ecosystems. In addition to climate change, the region's ecosystems are also influenced by several other impacts of human activities, such as chemical pollution, invasive species, and increased shipping and industrial developments. The end result is cumulative and cascading impacts on ecosystems and societies in the area."); Arctic Council Secretariat (2017) EXPERT GROUP ON BLACK CARBON AND METHANE: SUMMARY OF PROGRESS AND RECOMMENDATIONS 2017, 17 ("Arctic shipping currently accounts for about 5 percent of black carbon emissions within the Arctic; absent emission controls, shipping emissions within the Arctic could double by 2030 under some projections of Arctic vessel traffic.").

[500] Arctic Council Secretariat (2017) EXPERT GROUP ON BLACK CARBON AND METHANE: SUMMARY OF PROGRESS AND RECOMMENDATIONS 2017, 4 ("All eight Arctic States and five Observer States (France, India, Italy, Spain and the United Kingdom) developed and submitted inventories of black carbon and methane emissions, as well as methane projections. Six out of eight Arctic States provided black carbon projections, along with the United Kingdom. For some countries, black carbon emission inventories or projections were developed for the first time in fulfillment of the commitment to do so under the Framework, a foundational step in the Framework's implementation.").

[501] Arctic Council Secretariat (2017) EXPERT GROUP ON BLACK CARBON AND METHANE: SUMMARY OF PROGRESS AND RECOMMENDATIONS 2017, 4 ("Because methane projections were on average updated in 2013/2014, they do not capture the significant additional emissions reductions that would result from implementation of policies subsequently announced by some Arctic States regarding oil/gas emissions. Consequently, the current projections show little change in the total methane emissions across all Arctic States between 2013 and 2030. Black carbon inventories submitted by Arctic States (which generally did not include wildfire or open burning emission sources) indicate that diesel engines are the largest source followed by residential emissions from biomass combustion. Although black carbon emissions from oil and gas flaring are not reported by all Arctic States, the Arctic Council's Arctic Monitoring and Assessment Programme (AMAP) has indicated that flaring is the second largest source of

black carbon emissions from Arctic States, mainly due to Russian Federation emissions. Most but not all Arctic States submitted projections. Assuming no change in emissions by those Arctic States that did not submit projections, black carbon emissions across Arctic States are collectively projected to decrease by 24 percent from 2013 levels by 2025. This decrease is due mainly to standards for new vehicle engines and retirement of older, higher-emitting vehicles. Significantly, many Arctic countries substantially cut their emissions of black carbon prior to 2013, and these reductions are already reflected in the baseline for the current projections.").

[502] Arctic Monitoring and Assessment Programme (AMAP) (2017) SNOW, WATER, ICE, AND PERMAFROST IN THE ARCTIC: SUMMARY FOR POLICYMAKERS, 18 ("The transformative changes underway in the Arctic will continue and in some cases accelerate until at least mid-century regardless of efforts to reduce emissions. Impacts from climate change are thus expected to intensify for at least the next three to four decades, creating a clear and urgent need for knowledge and strategies to help Arctic communities and global society adapt to new conditions and reduce vulnerabilities to expected impacts. Addressing major knowledge gaps will help ensure adaptation strategies are grounded in a solid understanding of potential impacts and interactions.").

[503] Arctic Monitoring and Assessment Programme (AMAP) (2017) SNOW, WATER, ICE, AND PERMAFROST IN THE ARCTIC: SUMMARY FOR POLICYMAKERS, 19 ("SWIPA 2017 demonstrates great advances in our understanding of changes in the Arctic cryosphere, but also reveals major knowledge gaps. It also identifies several unmet scientific goals and specific areas where more observations and research are needed. As awareness of Arctic climate change and its consequences has grown, a number of international organizations, such as the Intergovernmental Panel on Climate Change (IPCC), the World Meteorological Organization (WMO), and the International Council for Science (ICSU) through the International Arctic Science Committee (IASC), have become increasingly engaged in understanding the implications of Arctic change. Making advances in these areas will require international coordination; long-term commitments to funding; the application of traditional and local knowledge; engagement with stakeholders; and coordinated and enhanced observation networks.").

[504] Arctic Monitoring and Assessment Programme (AMAP) (2017) SNOW, WATER, ICE, AND PERMAFROST IN THE ARCTIC: SUMMARY FOR POLICYMAKERS, 19 ("Outreach and public sharing of information about Arctic climate change, its consequences, uncertainties, risks, adaptation options, and effects of emission reductions are key to informed governance and policy development.").

[505] United Nations Framework Convention on Climate Change, 9 May 1992, 1771 U.N.T.S. 107.

[506] Paris Agreement to the United Nations Framework Convention on Climate Change, 12 December 2015; *see also* UNFCCC, "What is the Paris Agreement?" (*last accessed* 26 August 2018) ("At COP 21 in Paris, on 12 December 2015, Parties to the UNFCCC reached a landmark agreement to combat climate change and to accelerate and intensify the actions and investments needed for a sustainable low carbon future. The Paris Agreement builds upon the Convention and – for the first time – brings all nations into a common cause to undertake take ambitious efforts to combat climate change and adapt to its effects, with enhanced support to assist developing countries to do so. As such, it charts a new course in the global climate effort.").

[507]UNFCCC, "The Paris Agreement" (*last accessed* 26 August 2018) ("The Paris Agreement entered into force on 4 November 2016, thirty days after the date on which at least 55 Parties to the Convention accounting in total for at least an estimated 55 % of the total global greenhouse gas emissions have deposited their instruments of ratification, acceptance, approval or accession with the Depositary.").

[508] Paris Agreement to the United Nations Framework Convention on Climate Change, 12 December 2015, Art. 21.

[509] UNFCCC, "Paris Agreement – Status of Ratification" (*last accessed* 31 August 2018) ("To this date, 180 Parties have ratified of 197 Parties to the Convention.").

[510] Paris Agreement to the United Nations Framework Convention on Climate Change, 12 December 2015, Art. 2(1)(a).

[511] Paris Agreement to the United Nations Framework Convention on Climate Change, 12 December 2015, Art. 4(1).

[512] Paris Agreement to the United Nations Framework Convention on Climate Change, 12 December 2015, Art. 4(2). Also, many countries submitted this information prior to Paris, at which time they were referred to Intended Nationally Determined Contributions (INDCs), and these agreements can be modified prior to ratification of the Paris Agreement. Rogelj J., *et al.* (2016) *Paris Agreement climate proposals need a boost to keep warming well below 2 °C*, NATURE 534:631–639, 631 ("In preparation of this agreement, countries submitted national plans that spell out their intentions for addressing the climate change challenge after 20202. These Intended Nationally Determined Contributions (INDCs) address a range of issues, which can relate to avoiding, adapting or coping with climate change, among other things. Nevertheless, targets and actions for reducing greenhouse gas (GHG) emissions

are core components. At this point, the INDCs are not final and can be modified up until the time the Paris Agreement is ratified.").

[513] Paris Agreement to the United Nations Framework Convention on Climate Change, 12 December 2015, Art. 4(9).

[514] Paris Agreement to the United Nations Framework Convention on Climate Change, 12 December 2015, Art. 4(3).

[515] Paris Agreement to the United Nations Framework Convention on Climate Change, 12 December 2015, Art. 13(7).

[516] Paris Agreement to the United Nations Framework Convention on Climate Change, 12 December 2015, Art. 14.

[517] *See generally* Fransen T., *et al.* (2017) ENHANCING NDCS BY 2020: ACHIEVING THE GOALS OF THE PARIS AGREEMENT, World Resources Institute (WRI).

[518] Fransen T., *et al.* (2017) ENHANCING NDCS BY 2020: ACHIEVING THE GOALS OF THE PARIS AGREEMENT, World Resources Institute (WRI), 17 ("Not all short-lived climate pollutants are included in the Kyoto basket of gases (see Figure B5.1). Specifically, black carbon and tropospheric ozone are not Kyoto gases (although ozone is a GHG). For accounting purposes, Kyoto gases and non-Kyoto SLCPs should be treated separately in NDC goals and targets. In other words, economy-wide GHG goals should include only Kyoto gases, even if SLCPs are addressed separately. Many NDCs do not yet include all Kyoto gases and/or do not yet explicitly address short-lived climate pollutants, offering an opportunity to enhance ambition and implementation while capturing health benefits by including these substances. In this paper, enhancements involving GHG targets refer to targets covering Kyoto gases.").

[519] Schleussner C.-F., *et al.* (2016) *Science and policy characteristics of the Paris Agreement temperature goal*, NATURE CLIMATE CHANGE 6:827–835, 827 ("Here, we present an overview of science and policy aspects related to this goal and analyse the implications for mitigation pathways. We show examples of discernible differences in impacts between 1.5 °C and 2 °C warming. At the same time, most available low emission scenarios at least temporarily exceed the 1.5 °C limit before 2100. The legacy of temperature overshoots and the feasibility of limiting warming to 1.5 °C, or below, thus become central elements of a post-Paris science agenda. The near-term mitigation targets set by countries for the 2020–2030 period are insufficient to secure the achievement of the temperature goal.").

[520] Rogelj J., *et al.* (2016) *Paris Agreement climate proposals need a boost to keep warming well below 2 °C*, NATURE 534:631–639, 634 ("Under these assumptions of continued climate action, the 2030 unconditional-INDC emission range is roughly consistent with a median warming relative to pre-industrial levels of 2.6–3.1 °C (median, 2.9 °C; full scenario projection uncertainty, 2.2–3.5 °C…), with warming continuing its increase afterwards. This is an improvement on the current-policy and no-policy baseline scenarios, whose median projections suggest about 3.2 °C and more than 4 °C of temperature rise by 2100, respectively.").

[521] Schleussner C.-F., *et al.* (2016) *Science and policy characteristics of the Paris Agreement temperature goal*, NATURE CLIMATE CHANGE 6:827–835, 831 ("Key differences between 1.5 °C and 2 °C scenarios tend to be related to energy efficiency and more rapid near-term reductions.").

[522] Peters G. P., *et al.* (2017) *Key indicators to track current progress and future ambition of the Paris Agreement*, NATURE CLIMATE CHANGE 7:118–122, 120–121 ("Future changes in the carbon intensity of energy will be driven by the development and deployment of alternative technologies. Scenarios consistent with the Paris goal require a decreasing fossil-fuel share in energy use. Despite the large increase in fossil energy use in the past decades, current fossil energy trends remain consistent with many 2ºC scenarios. For this consistency to continue, declines in fossil energy, particularly coal, need to be initiated soon, particularly given existing infrastructure lock-in.").

[523] Peters G. P., *et al.* (2017) *Key indicators to track current progress and future ambition of the Paris Agreement*, NATURE CLIMATE CHANGE 7:118–122, 121 ("The relatively high fossil energy use in many 2ºC scenarios is predicated on large-scale deployment of CCS. In addition, most scenarios require strong growth in bioenergy, a large share of which is linked with CCS for carbon dioxide removal. It is uncertain whether bioenergy can be sustainably produced and made carbon-neutral at the scales required. Compounding this, without large-scale CCS deployment, most models cannot produce emission pathways consistent with the 2ºC goal.").

[524] Peters G. P., *et al.* (2017) *Key indicators to track current progress and future ambition of the Paris Agreement*, NATURE CLIMATE CHANGE 7:118–122, 121 ("Despite its importance, CCS deployment has continued to lag behind expectations. Emission scenarios require a rapid ramp-up of CCS facilities, potentially 4000 facilities by 2030, compared to the tens currently proposed by 2020. Given the lack of focus on CCS in emission pledges, a globally coordinated effort is needed to accelerate progress, better understand the technological risks, and address social acceptability.").

[525] Peters G. P., *et al.* (2017) *Key indicators to track current progress and future ambition of the Paris Agreement*, NATURE CLIMATE CHANGE 7:118–122, 121 ("Renewable energies are currently tracking well with the requirements of most 2ºC emission scenarios.").

[526] Peters G. P., *et al.* (2017) *Key indicators to track current progress and future ambition of the Paris Agreement*, NATURE CLIMATE CHANGE 7:118–122, 122 ("Current trends in many indicators appear broadly consistent with many of the emission scenarios that limit warming to well below 2ºC, but this masks four critical issues. First, studies clearly show that up to 2030, current emission pledges quickly deviate from what is required to be consistent with the Paris goal. Second, current trends of some key technologies (for example, CCS) deviate substantially from long-term requirements to meet the Paris goal. Third, if some technologies lag considerably behind expectations or requirements, then other technologies will need more rapid deployment and higher penetration levels into energy systems, a particularly important constraint for carbon dioxide removal. Fourth, there is the lack of scenarios exploring opportunities and challenges of transformational lifestyle and behavioural changes, low CCS and high renewables, alternative forms of carbon dioxide removal and solar radiation management.").

[527] Rogelj J., *et al.* (2016) *Paris Agreement climate proposals need a boost to keep warming well below 2 °C*, NATURE 534:631–639, 636 ("The post-2030 challenge to limit warming to below 2 °C from current INDC levels is daunting, and pursuing efforts for 1.5 °C even more so. However, the overall challenge can be minimized by additional GHG reductions in the near-term. In this context, near-term means before and by 2030. Besides (i) the option of countries increasing the overall ambition of their INDCs, we identify several other options that can contribute to this (see Table 2 for an overview). The options include: (ii) increasing the coverage of INDCs to more sectors and gases; (iii) including international sectors such as aviation and international maritime transport; (iv) implementing measures that enable over-delivery on the INDCs; (v) increasing contributions to international climate finance and international cooperation on technology development, transfer and diffusion; and (vi) promoting and implementing additional national, sub-national and non-state initiatives.").

[528] Schellnhuber H. J., *et al.* (2016) *Why the right climate target was agreed in Paris*, NATURE CLIMATE CHANGE 6:649–653, 651 ("We think that a better chance to deliver on the Paris promises can be generated by an alternative and more plausible route: in order to avoid the need to recourse to negative emissions as a late-regrets magic bullet (with questionable outcome), renewable energies and efficiency technologies could be scaled up exponentially, more rapidly than envisaged in the integrated assessment models behind the IPCC scenarios. We expect that such a 'technical explosion' will be matched by an 'induced implosion' of the incumbent industrial metabolism nourished by coal, oil, and gas.").

[529] Schellnhuber H. J., *et al.* (2016) *Why the right climate target was agreed in Paris*, NATURE CLIMATE CHANGE 6:649–653, 650 ("From Fig. 1 it is immediately apparent that even if global warming is limited to below 2 °C, some important tipping elements may already be harmed or transformed. In fact, the tipping point for marine ice sheet instability in the Amundsen Basin of West Antarctica may well have been crossed already, and the risk of crossing further tipping points will increase with future warming.").

[530] Velders G. J. M., *et al.* (2012) *Preserving Montreal Protocol Climate Benefits by Limiting HFCs*, SCIENCE 335:922–923, 922 ("With CFC phaseout completed in 2010 and the scheduled phaseout of most HCFCs by 2030, HFCs are being used more in applications that traditionally used ODSs, e.g., refrigeration and air-conditioning equipment, blowing agents for foams, aerosol sprays, fire protection systems, and solvents. The atmospheric abundances of major HFCs used as ODS substitutes are increasing 10 to 15% per year in recent years. Rising use of HFCs is directly attributable to intent and actions of the Montreal Protocol, hence, the HFC contribution to climate change can be viewed as an unintended negative side effect of these actions. The current contribution to climate forcing of HFCs used as ODS substitutes is about 0.012 W/m^2 [excluding HFC-23], less than 1% of the total forcing from long-lived GHGs, but it is increasing rapidly. Growth rates and projections indicate potential for substantial future increases in emissions and atmospheric abundances of HFCs in the absence of new controls. These business-as-usual projections are based on increasing demand for ODS substitutes, particularly in developing countries. In an upper-range scenario, global radiative forcing from HFCs increases from about 0.012 W/m^2 in 2010 to 0.25 to 0.40 W/m^2 in 2050…. This corresponds to 14 to 27% of the increase in CO_2 forcing under the range of Intergovernmental Panel on Climate Change (IPCC) business-as-usual scenarios from 2010 to 2050. In these scenarios, developing countries replace HCFCs with HFCs by using the same substances and use patterns as adopted by developed countries.").

[531] Molina M., *et al.* (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, 20617 ("The Montreal Protocol is widely considered the most successful environmental treaty, phasing out almost 100 ozone-depleting chemicals by 97% and placing the ozone layer on the path to recovery by mid-century. It also is the most

successful climate treaty to date, because chlorofluorocarbons (CFCs) and most other ozone-depleting substances (ODSs) that it has phased out are powerful GHGs with high GWPs that contribute 12% of the radiative forcing from long-lived GHGs and 20% of net anthropogenic forcing in 2005. From 1990 to 2010, the Montreal Protocol's controls on production and consumption of ODSs will have reduced GHG emissions by the equivalent of a net 135 Gt CO_2, which is equivalent to 11 Gt CO_2 per year. Considering only the direct warming effect, these actions of the Montreal Protocol delayed the increase in climate forcing from CO_2 by 7–12 years. The total delay in climate forcing is 31–45 years, when early voluntary and national actions to reduce ODSs are included, beginning with the early warning in 1974. Without early action, ODS emissions would have reached an estimated equivalent of 24–76 Gt CO_2 per year in 2010, and these emissions would have contributed nearly as much radiative forcing as anthropogenic emissions of CO_2.").

[532] UNEP (2016) REPORT OF THE TWENTY-EIGHTH MEETING OF THE PARTIES TO THE MONTREAL PROTOCOL ON SUBSTANCES THAT DEPLETE THE OZONE LAYER, UNEP/OzL.Pro.28/12, Decision XXVIII/1: Further Amendment to the Montreal Protocol.

[533] World Meteorological Organization (WMO) (2018) SCIENTIFIC ASSESSMENT OF OZONE DEPLETION: 2018, Global Ozone Research and Monitoring Project–Report No. 58, 2.41, Figure 2-20; *see also* Xu Y., *et al.* (2013) *The role of HFCs in mitigating 21st century climate change*, ATMOS. CHEM. PHYS. 13:6083–6089, 6083 ("Here we show that avoiding production and use of high-GWP (global warming potential) HFCs by using technologically feasible low-GWP substitutes to meet the increasing global demand can avoid as much as another 0.5ºC warming by the end of the century. This combined mitigation of 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 2ºC warming threshold during this century.").

[534] UNEP (2016) REPORT OF THE TWENTY-EIGHTH MEETING OF THE PARTIES TO THE MONTREAL PROTOCOL ON SUBSTANCES THAT DEPLETE THE OZONE LAYER, UNEP/OzL.Pro.28/12, Decision XXVIII/1: Further Amendment to the Montreal Protocol; *see also* BULLETIN OF THE ATOMIC SCIENTISTS, D. J. Zaelke, "Global agreement addressing ozone depletion will also bring large climate benefits" (2 January 2019).

[535] Shah N., *et al.* (2015) BENEFITS OF LEAPFROGGING TO SUPEREFFICIENCY AND LOW GLOBAL WARMING POTENTIAL REFRIGERANTS IN AIR CONDITIONING, Ernest Orlando Lawrence Berkeley National Laboratory, 3 ("Beginning in the 1990's, the Montreal Protocol successfully targeted the phase-out of all manufactured ozone-depleting substances (ODSs), including chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), chemicals used as refrigerants in most air conditioning and refrigeration appliances and equipment. CFCs and HCFCs are both ozone depleting substances (ODSs) and potent global warming gases. The global phase-out of CFCs is now complete in all developing and developed countries. Developed countries have additionally phased out 90% of HCFC production and consumption by 2015 and will halt all HCFC use other than service by 2030. Developing countries began their HCFC phase-out with a freeze in 2013 and a 10% reduction in 2015 and will make further reductions to 35% in 2020, 67.5 in 2025, 97.5% in 2030 and 100% in 2040. This phase-out schedule for developing Parties offers the opportunity to leapfrog directly to superefficient air conditioners that also use an ozone-safe, low-GWP alternative refrigerants.").

[536] UNEP (2016) REPORT OF THE TWENTY-EIGHTH MEETING OF THE PARTIES TO THE MONTREAL PROTOCOL ON SUBSTANCES THAT DEPLETE THE OZONE LAYER, UNEP/OzL.Pro.28/12, Decision XXVIII/1: Further Amendment to the Montreal Protocol. The Kigali Amendment does not completely phase out HFCs but will make progress to phase down HFCs.

[537] Climate and Clean Air Coalition (CCAC) (2014) LOW-GWP ALTERNATIVES IN COMMERCIAL REFRIGERATION: PROPANE, CO_2, AND HFO CASE STUDIES, 5 ("Research was conducted to generate a list of potential case studies for consideration taking into account all of the currently available zero- and low-GWP refrigerants in commercial refrigeration applications, including "natural" refrigerants, such as hydrocarbons, carbon dioxide (CO_2), and ammonia, as well as the other major category of alternatives comprising man-made chemicals such as the unsaturated HFCs known as hydrofluoroolefins (HFOs). HFOs are a new class of unsaturated HFC refrigerants which have lower GWPs and shorter atmospheric lifetimes when compared to other HFCs.").

[538] Shah N., *et al.* (2015) BENEFITS OF LEAPFROGGING TO SUPEREFFICIENCY AND LOW GLOBAL WARMING POTENTIAL REFRIGERANTS IN AIR CONDITIONING, Ernest Orlando Lawrence Berkeley National Laboratory, ES-9 ("While there is some uncertainty associated with emissions and growth projections, moving to efficient room air conditioning (~30% more efficient than current technology) in parallel with low-GWP refrigerants in room air conditioning could avoid upto ~25 billion tonnes of CO_2 in 2030, ~33 billion in 2040, and ~40 billion in 2050, i.e. cumulative savings upto 98 billion tonnes of CO_2 by 2050.").

[539] Velders G. J. M., *et al.* (2014) *Growth of climate change commitments from HFC banks and emissions*, ATMOS. CHEM. PHYS. 14:4563–4572, 4568 ("Because of the consistently increasing HFC production through 2050, the earlier the phaseout, the shorter is the period the banks can build up and the smaller is the final bank size at the phaseout date. If, for example, the HFC production were to be phased out in 2020 instead of 2050, the cumulative emissions avoided would be about 91–146 $GtCO_2$-eq from 2020 to 2050, while a bank of about 39–64 $GtCO_2$-eq is also avoided in 2050, an additional benefit to climate protection of about 40 % compared with the cumulative emissions reduction alone. This comparison exemplifies how an analysis that, for example, just examines emissions and radiative forcing time series through 2050 would understate the full climate benefits of an earlier HFC production phaseout.").

[540] UNECE (2012) DECISION 2012/2 AMENDMENT OF THE TEXT OF AND ANNEXES II TO IX TO THE 1999 PROTOCOL TO ABATE ACIDIFICATION, EUTROPHICATION AND GROUND-LEVEL OZONE AND THE ADDITION OF NEW ANNEXES X AND XI; *see also* UN Economic Commission for Europe (UNECE), "Protocol to Abate Acidification, Eutrophication and Ground-level Ozone" (*last accessed* 16 April 2018) ("The Protocol was amended in 2012 by Executive Body decisions 2012/1 and 2012/2 to include national emission reduction commitments to be achieved by 2020 and beyond. Several of the Protocol's technical annexes were revised with updated sets of emission limit values for both key stationary sources and mobile sources. The revised Protocol is also the first binding agreement to include emission reduction commitments for fine particulate matter. Also for the first time, the Parties have broken new ground in international air pollution policy by specifically including the short-lived climate pollutant black carbon (or soot) as a component of particular matter. Reducing particulate matter (including black carbon) through the implementation of the Protocol is thus a major step in reducing air pollution, while at the same time facilitating climate co-benefits.").

[541] Climate & Clean Air Coalition (CCAC), "Who we are" (*last accessed* 3 June 2018) ("The Climate and Clean Air Coalition is a voluntary partnership of governments, intergovernmental organizations, businesses, scientific institutions and civil society organizations committed to improving air quality and protecting the climate through actions to reduce short-lived climate pollutants. Our global network currently includes over 120 state and non-state partners, and hundreds of local actors carrying out activities across economic sectors. …In 2012, the governments of Bangladesh, Canada, Ghana, Mexico, Sweden and the United States, along with the United Nations Environment Programme (UNEP), came together to initiate efforts to treat short-lived climate pollutants as an urgent and collective challenge. Together, they formed the Climate & Clean Air Coalition to support fast action and deliver benefits on several fronts at once: climate, public health, energy efficiency, and food security.").

[542] Climate & Clean Air Coalition (CCAC), "Initiatives" (*last accessed* 3 June 2018).

[543] Climate & Clean Air Coalition (CCAC), "What we do" (*last accessed* 3 June 2018) ("The Coalition's partners and initiative participants work in cooperation with key short-lived climate pollutant emitters and other stakeholders from around the world to encourage, enable and catalyze action to reduce emissions. To achieve real and ambitious reductions, the Coalition focuses on four key strategies: Enable transformative action by providing knowledge, resources, and technical and institutional capacity to act and supporting the sharing of information, experience, and expertise. Mobilize support for action to put short-lived climate pollutants on the policy map through advocacy at all levels of government and in the private sector and civil society. Increase the availability of and access to financial resources to support the successful implementation of scalable, transformational action. Enhance scientific knowledge to help decision-makers scale up action and promote the multiple benefits of action on short-lived climate pollutants.").

[544] Climate & Clean Air Coalition (CCAC), "What we do" (*last accessed* 3 June 2018) ("The Coalition takes action through initiatives, which are partner-led and designed to provide transformative action in sectors or as cross-cutting efforts to reduce methane, black carbon and hydrofluorocarbons (HFCs). These actions include: Training and institutional strengthening; Support for developing laws, regulations, policies and plans; Technology demonstrations; Political outreach; Awareness raising campaigns; Co-funding and catalysed funding; Development of knowledge resources and tools.").

[545] Climate & Clean Air Coalition (CCAC) (2017) ANNUAL REPORT: 2016–2017.

[546] *See, e.g.*, Climate & Clean Air Coalition (CCAC) (2017) *Cooling & Refrigeration (HFC) Initiative progress report: 2016–2017*; *and* Climate & Clean Air Coalition (CCAC) (2017) *Diesel Initiative progress report: 2016–2017*.

[547] Climate & Clean Air Coalition (CCAC) (2015) *Five-Year Strategic Plan*.

[548] Climate & Clean Air Coalition (CCAC) (2015) *Five-Year Strategic Plan*.

[549] Climate & Clean Air Coalition (CCAC) (2017) *Bonn Communique*.

[550] International Maritime Organization (IMO), "Brief History of IMO" (*last accessed* 19 September 2018) ("Several countries proposed that a permanent international body should be established to promote maritime safety more effectively, but it was not until the establishment of the United Nations itself that these hopes were realized. In 1948 an international conference in Geneva adopted a convention formally establishing IMO (the original name was the Inter-Governmental Maritime Consultative Organization, or IMCO, but the name was changed in 1982 to IMO). The IMO Convention entered into force in 1958 and the new Organization met for the first time the following year.").

[551] Convention on the Intergovernmental Maritime Consultative Organization, 6 March 1948, 289 U.N.T.S. 48, Art. 1; *see also* International Maritime Organization (IMO), "Brief History of IMO" (*last accessed* 19 September 2018) ("The purposes of the Organization, as summarized by Article 1(a) of the Convention, are 'to provide machinery for cooperation among Governments in the field of governmental regulation and practices relating to technical matters of all kinds affecting shipping engaged in international trade; to encourage and facilitate the general adoption of the highest practicable standards in matters concerning maritime safety, efficiency of navigation and prevention and control of marine pollution from ships'. The Organization is also empowered to deal with administrative and legal matters related to these purposes.").

[552] International Maritime Organization (IMO), "Brief History of IMO" (*last accessed* 19 September 2018) ("IMO's first task was to adopt a new version of the International Convention for the Safety of Life at Sea (SOLAS), the most important of all treaties dealing with maritime safety. This was achieved in 1960 and IMO then turned its attention to such matters as the facilitation of international maritime traffic, load lines and the carriage of dangerous goods, while the system of measuring the tonnage of ships was revised.").

[553] International Maritime Organization (IMO), "Brief History of IMO" (*last accessed* 19 September 2018) ("The most important of all these measures was the International Convention for the Prevention of Pollution from Ships, 1973, as modified by the Protocol of 1978 relating thereto (MARPOL 73/78). It covers not only accidental and operational oil pollution but also pollution by chemicals, goods in packaged form, sewage, garbage and air pollution.").

[554] International Maritime Organization (IMO) "International Convention for the Prevention of Pollution from Ships (MARPOL) – Adoption: 1973 (Convention), 1978 (1978 Protocol), 1997 (Protocol - Annex VI); Entry into force: 2 October 1983 (Annexes I and II)" (*last accessed* 19 September 2018) ("In 1997, a Protocol was adopted to amend the Convention and a new Annex VI was added which entered into force on 19 May 2005. MARPOL has been updated by amendments through the years. The Convention includes regulations aimed at preventing and minimizing pollution from ships - both accidental pollution and that from routine operations - and currently includes six technical Annexes. Special Areas with strict controls on operational discharges are included in most Annexes.").

[555] International Maritime Organization (IMO) "International Convention for the Prevention of Pollution from Ships (MARPOL) – Adoption: 1973 (Convention), 1978 (1978 Protocol), 1997 (Protocol - Annex VI); Entry into force: 2 October 1983 (Annexes I and II)" (*last accessed* 19 September 2018) ("Annex VI Prevention of Air Pollution from Ships (entered into force 19 May 2005): Sets limits on sulphur oxide and nitrogen oxide emissions from ship exhausts and prohibits deliberate emissions of ozone depleting substances; designated emission control areas set more stringent standards for SOx, NOx and particulate matter. A chapter adopted in 2011 covers mandatory technical and operational energy efficiency measures aimed at reducing greenhouse gas emissions from ships."); *see also* International Maritime Organization (IMO) (1998) *MARPOL – 25 Years*, 27 ("Annex VI on Regulations for the Prevention of Air Pollution from Ships, when it comes into force, will set limits on sulphur oxide and nitrogen oxide emissions from ship exhausts and prohibit deliberate emissions of ozone depleting substances.").

[556] United Nations Conference on Trade and Development (2017) REVIEW OF MARITIME TRANSPORT—2017, 90 ("With regard to NOx, the Marine Environment Protection Committee adopted amendments designating the North Sea and the Baltic Sea (which are emission control areas for sulphur oxide (SOx)) as NOx emission control areas under the International Convention for the Prevention of Pollution from Ships, annex VI, regulation 13. Marine diesel engines operating in these areas will be required to comply with the stricter tier III NOx emissions limit when installed on ships constructed on or after 1 January 2021. Guidelines on selective catalytic reduction systems were also adopted (IMO, 2017c, annex 13)."); *see also* International Maritime Organization (IMO), "Emission Control Areas (ECAs) designated under MARPOL Annex VI" (*last accessed* 19 September 2018).

[557] United Nations Conference on Trade and Development (2017) REVIEW OF MARITIME TRANSPORT—2017, 90 ("With regard to SOx, the Committee adopted an important decision with regard to human health and the environment, namely to implement a global limit of 0.5 per cent on sulphur in fuel oil used on board ships, as set out in the International Convention for the Prevention of Pollution from Ships, annex VI, regulation 14.1.3, from 1 January 2020 (IMO, 2016a, annex 6). This represents a significant reduction from the 3.5 per cent limit currently in

place outside emission control areas.8 To meet requirements, shipowners and operators continue to adopt various strategies, including installing scrubbers and switching to liquefied natural gas and other low-sulphur fuels. The Committee approved guidelines providing an agreed method for sampling to enable the effective control and enforcement of sulphur content of liquid fuel oil used on board ships under the provisions of the International Convention for the Prevention of Pollution from Ships, annex VI (IMO, 2016b), and amendments to the information to be included in the bunker delivery note related to the supply of fuel oil to ships that have fitted alternative mechanisms to address SOx emission requirements (IMO, 2017c)."); *see also* International Maritime Organization (IMO), "Emission Control Areas (ECAs) designated under MARPOL Annex VI" (*last accessed* 19 September 2018).

558 UNEP & WMO (2011) INTEGRATED ASSESSMENT OF BLACK CARBON AND TROPOSPHERIC OZONE, 40 ("At present, Arctic shipping contributes 1–3 per cent to global shipping emissions, depending on the pollutant, but its proximity to sensitive ecosystems might make it a much more important source locally in the future, especially when an extended period of ice-free.").

559 Arctic Monitoring and Assessment Programme (AMAP) (2015) SUMMARY FOR POLICYMAKERS: ARCTIC CLIMATE ISSUES 2015 SHORT-LIVED CLIMATE POLLUTANTS, 7 ("While only about one percent of global anthropogenic emissions occur north of 60°N, and only a tenth of that comes from sources north of 70°N, black carbon emissions from Arctic States have greater impacts because they are closer to the Arctic. Within the Arctic, shipping currently accounts for about 5% of black carbon emissions, but could double by 2030 and quadruple by 2050 under some projections of Arctic vessel traffic. Flaring of excess natural gas at oil and gas fields, an alternative to releasing methane straight to the atmosphere, could account for two-thirds of Arctic emissions of black carbon, and typically also results in emissions of methane from incomplete combustion.").

560 International Council on Clean Transportation (ICCT) (2017) GREENHOUSE GAS EMISSIONS FROM GLOBAL SHIPPING, 2013–2015, v ("After CO_2, black carbon (BC) contributes the most to the climate impact of shipping, representing 7% of total shipping CO_2-eq emissions on a 100-year timescale and 21% of CO_2-eq emissions on a 20-year time scale (Figure ES-3). Because BC is a short-lived climate pollutant, reducing BC emissions from ships would immediately reduce shipping's climate impacts. Until now, BC has been largely ignored as a climate pollutant from ships. In this study, we report the "missing inventory" of BC emissions that ought to be considered when evaluating the climate impacts of shipping.").

561 CARBON BRIEF, J. Timperley, *In-depth: Will countries finally agree a climate deal for shipping?* (6 April 2018) ("The shipping industry emitted 932 million tonnes of CO_2 in 2015, according to a recent report from the International Council on Clean Transportation (ICCT). This corresponded to around 2.6% of global energy-related CO_2 emissions, up from around 2.2% in 2012.").

562 CARBON BRIEF, J. Timperley, *In-depth: Will countries finally agree a climate deal for shipping?* (6 April 2018) ("The IMO's most recent study on international shipping emissions estimated they could grow between 50% and 250% by 2050, under current measures. As other sectors are set to decarbonise, this means shipping could grow to represent an ever larger portion of global emissions if not cap is set.").

563 CARBON BRIEF, J. Timperley, *In-depth: Will countries finally agree a climate deal for shipping?* (6 April 2018) ("According to the ICCT, warming due to black carbon is equivalent to 7% of the sector's GHG emissions on a 100-year timescale, but 21% on a 20-year time scale. This means reducing black carbon would have a rapid effect on shipping's contribution to global warming.").

564 Sand M., *et al.* (2013) *Arctic surface temperature change to emissions of black carbon within Arctic or midlatitudes*, J. GEOPHYSICAL RESEARCH 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., *et al.* (2013) *Black carbon in the Arctic: the underestimated role of gas flaring and residential combustion emissions*, ATMOS. CHEM. PHYS. 13:8833–8855, 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.).

565 Arctic Council Task Force on Short-Lived Climate Forcers (2013) RECOMMENDATIONS TO REDUCE BLACK CARBON AND METHANE EMISSIONS TO SLOW ARCTIC CLIMATE CHANGE, 6 ("Marine shipping emissions [of black carbon] are currently not large in the polar region, but are expected to grow with increasing resource extraction and tourism activity. …Black carbon emissions from shipping and oil and gas operations within the Arctic are expected to increase, but to what degree is uncertain. Increased emissions from these sources could have strong climatic

impacts given their proximity to Arctic snow and ice. In several Arctic nations, residential combustion is projected to remain or become the key anthropogenic source of black carbon.").

[566] Comer B. (2018) HEAVY FUEL OIL USE IN THE IMO POLAR CODE ARCTIC SUMMARIZED BY FLAG STATE, 2015, 5 ("In 2015 in the IMO Arctic, 2,086 ships operated for 2.6 million hours, traveling 10.3 million nautical miles, with 1.1 million tonnes of fuel onboard, collectively, at any given time. These ships consumed 436 thousand tonnes of fuel and emitted 193 tonnes of BC. As shown in Figure 2, 889 of the 2,089 ships, or 42%, operated on HFO in the IMO Arctic in 2015. HFO represented 57% of fuel use by weight, 76% of fuel carried by weight, and 56% of distance-weighted fuel carried. In total, 68% of the 193 tonnes of BC these ships emitted resulted from burning HFO.").

[567] Comer B. (2018) HEAVY FUEL OIL USE IN THE IMO POLAR CODE ARCTIC SUMMARIZED BY FLAG STATE, 2015, 9–11, Table A-1.

[568] Stephenson S. R., *et al.* (2018) *Climatic responses to future trans-Arctic shipping*, GEOPHYSICAL RESEARCH LETTERS 45:9898–9908, 9905 ("However, even as the Arctic continues to warm at twice the rate of the global average, we find that the net regional climatic impact of trans-Arctic shipping emissions will likely be less warming. This is because in contrast to previous studies, increased BC emissions do not cause significant warming in our simulations relative to cloud radiative effects, in line with minor BC radiative forcing found in the Arctic from in situ measurements (0.06 W/m^2) and previous model simulations (0.51 W/m^2; Dang et al., 2017; Qian et al., 2014). Instead, aerosol direct effects are offset by reduced water vapor enabling increased shortwave downwelling and reduced surface albedo from BC is counteracted by substantial increases in cloud albedo. In short, cooling driven by sulfate-induced liquid cloud formation dominates in our experiment. However, we emphasize that the magnitude of this cooling effect (~1 °C) is roughly an order of magnitude smaller than the overall regional warming in RCP 8.5 (~10 °C). Although the CESM model that we use is more sophisticated than those used in prior studies, it is possible that the cooling we simulate may reflect enhanced liquid water path caused by a large decrease in the rate of conversion of cloud to rainwater when cloud droplet number increases (Wang et al., 2013; Zhou & Penner, 2017).").

[569] Stephenson S. R., *et al.* (2018) *Climatic responses to future trans-Arctic shipping*, GEOPHYSICAL RESEARCH LETTERS 45:9898–9908, 9898 ("As global temperatures increase, sea ice loss will increasingly enable commercial shipping traffic to cross the Arctic Ocean, where the ships' gas and particulate emissions may have strong regional effects. Here we investigate impacts of shipping emissions on Arctic climate using a fully coupled Earth system model (CESM 1.2.2) and a suite of newly developed projections of 21st-century trans-Arctic shipping emissions. We find that trans-Arctic shipping will reduce Arctic warming by nearly 1 °C by 2099, due to sulfate-driven liquid water cloud formation. Cloud fraction and liquid water path exhibit significant positive trends, cooling the lower atmosphere and surface. Positive feedbacks from sea ice growth-induced albedo increases and decreased downwelling longwave radiation due to reduced water vapor content amplify the cooling relative to the shipping-free Arctic. Our findings thus point to the complexity in Arctic climate responses to increased shipping traffic, justifying further study and policy considerations as trade routes open.").

[570] Stephenson S. R., *et al.* (2018) *Climatic responses to future trans-Arctic shipping*, GEOPHYSICAL RESEARCH LETTERS 45:9898–9908, 9899 ("Other mechanisms of radiative forcing are also important to Arctic temperatures. The insulating effect of longwave absorption by clouds may amplify Arctic warming (Cox et al., 2015), and Arctic clouds are particularly sensitive to increases in cloud condensation nuclei (CCN) from pollution due to the stability of Arctic air masses (Coopman et al., 2018). In opposition, emissions of sulfur oxides (SO_2) and resulting sulfate (SO_4) generate a direct negative radiative forcing by scattering incoming sunlight (Charlson et al., 1992), which may offset a significant part of the BC heating effect in the Arctic (Yang et al., 2018). Lastly, an increase in atmospheric particulates that serve as CCN will tend to increase cloud albedo by encouraging formation of smaller and more numerous cloud droplets (Twomey, 1977), particularly in liquid clouds (Christensen et al., 2014; Morrison et al., 2012). Although the influence of particulate emissions in the Arctic has historically been small and localized relative to more populous lower latitudes (Gong et al., 2018; Peters et al., 2011), increases in shipping emissions could substantially raise CCN, enhance cloud formation, and induce a climatic response (Mueller, 2018; Wang et al., 2013; Yang et al., 2018).").

[571] Stephenson S. R., *et al.* (2018) *Climatic responses to future trans-Arctic shipping*, GEOPHYSICAL RESEARCH LETTERS 45:9898–9908, 9902 ("Our experiment demonstrates a clear and small yet significant slowing of Arctic warming as a result of trans-Arctic shipping emissions. Figure 2 shows that by 2099, sea surface temperature (SST) north of 66.5°N is nearly 1 °C cooler, and sea ice extent greater by nearly 500,000 km^2, in the experiment runs compared to the LENS control. The shipping-induced cooling (~1 °C) is a small fraction of net RCP8.5 warming (~10 °C), comparable in magnitude (though opposite in sign) to Arctic warming from anthropogenic CH_4 scaled to the LENS control results over the same period, based on CH_4 effective radiative forcing (IPCC, 2013)."); *see also*

Aksenov Y., *et al.* (2017) *On the future navigability of Arctic sea routes: High-resolution projections of the Arctic Ocean and sea ice*, MARINE POLICY 75:300–317, 313 ("Another caveat is that, while the shift of shipping to shorter Arctic routes may decrease fuel use and lower CO_2 emissions, the impact on climate warming may not be wholly negative. This is because the use of Arctic routes may lead to increased concentrations of non-CO_2 gases, aerosols and particles in the Arctic, which can change radiative forcing (e.g. deposition of black carbon on sea ice and snow) and produce more complex regional warming/cooling effects. Simulations of these aspects of Arctic routes suggest that there may actually be a net global warming effect before net cooling takes over, thus suggesting that changes in the Arctic maritime use could potentially affect the global economy and global natural environment.").

[572] Stephenson S. R., *et al.* (2018) *Climatic responses to future trans-Arctic shipping*, GEOPHYSICAL RESEARCH LETTERS 45:9898–9908, 9906 ("As shipping will likely contribute a minor share of the total Arctic aerosol emissions by midcentury (Browse et al., 2013), BC from such coastal sources may counteract the cooling effect from enhanced clouds. Furthermore, planned global limits on ships' SO_2 emissions after 2020 (IMO, 2018) will reduce aerosol cooling from shipping in much the same way that air quality improvements since the 1970s have unmasked GHG warming in urban areas. In this way, the net climatic impact of Arctic shipping will ultimately depend on international regulatory and trade agreements in addition to marine access. Our results thus highlight a need for integrated analysis of climatic and transport systems to further clarify the reciprocal relationship of climate and human activities in the Arctic.").

[573] International Maritime Organization (IMO), "Shipping in polar waters – Adoption of an international code of safety for ships operating in polar waters (Polar Code)" (*last accessed* 20 September 2018) ("IMO has adopted the International Code for Ships Operating in Polar Waters (Polar Code) and related amendments to make it mandatory under both the International Convention for the Safety of Life at Sea (SOLAS) and the International Convention for the Prevention of Pollution from Ships (MARPOL). The Polar Code entered into force on 1 January 2017. This marks an historic milestone in the Organization's work to protect ships and people aboard them, both seafarers and passengers, in the harsh environment of the waters surrounding the two poles. The Polar Code and SOLAS amendments were adopted during the 94th session of IMO's Maritime Safety Committee (MSC), in November 2014; the environmental provisions and MARPOL amendments were adopted during the 68th session of the Marine Environment Protection Committee (MEPC) in May 2015.").

[574] International Maritime Organization (IMO) "Milestone for polar protection as comprehensive new ship regulations come into force" (1 January 2017) ("The mandatory Polar Code, for ships operating in Arctic and Antarctic waters, enters into force on 1 January 2017, marking a historic milestone in the work of the International Maritime Organization (IMO) to address this key issue. Its requirements, which were specifically tailored for the polar environments, go above and beyond those of existing IMO conventions such as MARPOL and SOLAS, which are applicable globally and will still apply to shipping in polar waters.").

[575] International Maritime Organization (IMO) (2014) INTERNATIONAL CODE FOR SHIPS OPERATING IN POLAR WATERS (POLAR CODE); *see also* International Maritime Organization (IMO) "Milestone for polar protection as comprehensive new ship regulations come into force" (1 January 2017) ("To address all these issues, the Polar Code sets out mandatory standards that cover the full range of design, construction, equipment, operational, training and environmental protection matters that apply to ships operating in the inhospitable waters surrounding the two poles. Protective thermal clothing, ice removal equipment, enclosed lifeboats and the ability to ensure visibility in ice, freezing rain and snow conditions are among the Code's mandatory safety requirements. The regulations extend to the materials used to build ships intended for polar operation, and all tankers under the Code will have to have double hulls. From an environmental perspective, the code prohibits or strictly limits discharges of oil, chemicals, sewage, garbage, food wastes and many other substances. The Polar Code will make operating in these waters safer, helping to protect the lives of crews and passengers. It will also provide a strong regime to minimise the impact of shipping operations on the pristine polar regions. It will be seen as a major achievement in IMO's work to promote safe and sustainable shipping in all regions of the world, including the most challenging and difficult.").

[576] International Maritime Organization (IMO), RESOLUTION MEPC.189(60)—AMENDMENTS TO THE ANNEX OF THE PROTOCOL OF 1978 RELATING TO THE INTERNATIONAL CONVENTION FOR THE PREVENTION OF POLLUTION FROM SHIPS, 1973, 26 March 2010.

[577] International Maritime Organization (IMO) (2014) INTERNATIONAL CODE FOR SHIPS OPERATING IN POLAR WATERS (POLAR CODE) ("Ships are encouraged to apply regulation 43 of MARPOL Annex I when operating in Arctic waters."); International Maritime Organization (IMO) "Shipping in polar waters – Adoption of an international code of safety for ships operating in polar waters (Polar Code)" (*last accessed* 19 September 2018) ("A MARPOL regulation, to protect the Antarctic from pollution by heavy grade oils, was adopted by the Marine Environment Protection Committee (MEPC), at its 60th session in March, 2010. The amendments entered into force

on 1 August 2011. The amendments add a new chapter 9 to MARPOL Annex I with a new regulation 43 which prohibits the carriage in bulk as cargo, or carriage and use as fuel, of: crude oils having a density at 15°C higher than 900 kg/m^3; oils, other than crude 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; or bitumen, tar and their emulsions. An exception is envisaged for vessels engaged in securing the safety of ships or in a search and rescue operation. Under the Polar Code ships are encouraged not to use or carry heavy fuel oil in the Arctic.").

[578] Press Release, International Maritime Organization, "Sub-Committee on Pollution Prevention and Response (PPR 6), 18-22 February 2019" (22 February 2019) ("The Sub-Committee began its work to develop measures to reduce the risks of use and carriage of heavy fuel oil as fuel by ships in Arctic waters. A working definition for heavy fuel oil was noted, which says that "heavy fuel oil means fuel oils having a density at 15ºC higher than 900 kg/m^3 or a kinematic viscosity at 50ºC higher than 180 mm^2/s". A draft methodology for analysing impacts of a ban on heavy fuel oil for the use and carriage as fuel by ships in Arctic waters was agreed. The Sub-Committee invited submissions to PPR 7, especially those by Arctic States, containing impact assessments guided by but not limited to the methodology. The methodology sets out five steps to assess the impact of a ban. Specific analyses that are detailed include: determination of the study area; assessment of the costs to Arctic indigenous and local communities and industries; assessment of the benefits of an HFO ban to Arctic indigenous and local communities and ecosystems; and consideration of other factors that could either ameliorate adverse impacts of a ban or accommodate specific situations. Meanwhile, a correspondence group was instructed to develop guidelines on measures to reduce risks of use and carriage of heavy fuel oil as fuel by ships in Arctic waters. The guidance could include sections on navigational measures; ship operations; infrastructure (onshore and offshore) and communications; enhanced preparedness for emergencies of oil spills, early spill detection and response; drills and training; and economic assessment of potential measures.").

[579] The April 2018 IMO meeting was the initial step in negotiations to reduce GHG emissions with the final step happening in 2023. NATURE, J. Tollefson, *Global negotiations set to limit greenhouse-gas pollution from ships* (6 April 2018) ("A panel of the United Nations International Maritime Organization (IMO) is due to meet in London, where it is expected to agree on a resolution that would set targets for emissions reductions and lay the groundwork for future regulations. The IMO would then flesh out and finalize the regulatory framework by 2023.").

[580] International Maritime Organization (IMO), "Marine Environment Protection Committee (MEPC), 72nd session, 9–13 April 2018" (13 April 2018) ("More specifically, under the identified "levels of ambition", the initial strategy envisages for the first time a reduction in total GHG emissions from international shipping which, it says, should peak as soon as possible and to reduce the total annual GHG emissions by at least 50% by 2050 compared to 2008, while, at the same time, pursuing efforts towards phasing them out entirely.").

[581] Wan Z., *et al.* (2016) *Pollution: Three steps to a green shipping industry*, NATURE 530:275–277, 276 ("Energy efficiency is the IMO's present focus. Starting in 2013, its Energy Efficiency Design Index and Ship Energy Efficiency Management Plan aim to lower CO_2 emissions from shipping through tighter technical requirements on engines and equipment, maintenance regimes and voyage plans. No absolute emissions-reduction targets were set. Unfortunately, long-term expansion in global trade and growing ship numbers mean that even if these measures are fully implemented, total shipping emissions are projected to quadruple from 1990 to 2050.").

[582] NATURE, J. Tollefson, *Global negotiations set to limit greenhouse-gas pollution from ships* (6 April 2018) ("One option currently under consideration calls for strengthening and extending energy-efficiency regulations that the IMO adopted in 2011. Other proposals could mandate cleaner fuels or new engine technologies, or impose new speed limits on ships in international waters to reduce fuel consumption. Another outstanding question is whether the shipping industry would be allowed to offset its greenhouse-gas emissions by purchasing carbon credits.").

[583] Wan Z., *et al.* (2016) *Pollution: Three steps to a green shipping industry*, NATURE 530:275–277, 276 ("The IMO has set up four 'emission-control areas' — the Baltic Sea, the North Sea, the US Caribbean and the coastal waters of Canada and the United States — where ships are required to minimize emissions mainly of SO_x and NO_x.").

[584] Press Release, International Maritime Organization, "Sub-Committee on Pollution Prevention and Response (PPR 6), 18-22 February 2019" (22 February 2019) ("The Sub-Committee identified a number of potential control measures to reduce the impact on the Arctic of Black Carbon emissions from international shipping. A simplified compilation of the identified control measures was forwarded to MEPC 74. The Committee was invited to provide instruction on further work on the reduction of the impact on the Arctic of Black Carbon emissions from international shipping.").

[585] Press Release, Maersk, "Maersk sets net zero CO_2 emission target by 2050" (4 December 2018) ("Aimed at accelerating the transition to carbon neutral shipping, Maersk announces today its goal to reach carbon neutrality by 2050. To achieve this goal, carbon neutral vessels must be commercially viable by 2030, and an acceleration in new

innovations and adaption of new technology is required. Climate is one of the most important issues in the world, and carrying around 80% of global trade, the shipping industry is vital to finding solutions. By now, Maersk´s relative CO2 emissions have been reduced by 46% (baseline 2007), approx. 9% more than the industry average. As world trade and thereby shipping volumes will continue to grow, efficiency improvements on the current fossil based technology can only keep shipping emissions at current levels but not reduce them significantly or eliminate them."); *see also* FINANCIAL TIMES, R. Milne, *Maersk pledges to cut carbon emissions to zero by 2050* (4 December 2018) ("The world's largest container shipping company has pledged to cut net carbon emissions to zero by 2050, challenging an industry that is both one of the main transporters of global trade and one of the biggest polluters to come up with radical solutions in the next decade. AP Moller Maersk, the Danish group that transports nearly one in five seaborne containers, said it needed its entire supply chain from engine makers and shipbuilders to new technology providers to come up with carbon-free ships by 2030 to meet the goal. …Maersk's target, although distant, is one of the most ambitious from a global industrial group promising to end carbon emissions altogether. Container ships carry about 80 per cent of global trade and currently use bunker fuel, a residue from crude oil that is cheaper but dirtier than petrol and diesel, which means they contribute about 3 per cent of the world's emissions.").

[586] Convention on International Civil Aviation, 7 December 1944, 15 U.N.T.S 295, Art. 43; *see also* International Civil Aviation Organization (ICAO), "About ICAO" (*last accessed* 17 September 2018) ("The International Civil Aviation Organization (ICAO) is a UN specialized agency, established by States in 1944 to manage the administration and governance of the Convention on International Civil Aviation (Chicago Convention).").

[587] International Civil Aviation Organization (ICAO), "Convention on International Civil Aviation - Doc 7300" (*last accessed* 17 September 2018) ("Convention on International Civil Aviation (also known as Chicago Convention), was signed on 7 December 1944 by 52 States. Pending ratification of the Convention by 26 States, the Provisional International Civil Aviation Organization (PICAO) was established. It functioned from 6 June 1945 until 4 April 1947. By 5 March 1947 the 26th ratification was received. ICAO came into being on 4 April 1947."). Presently, the ICAO has 192 member States. International Civil Aviation Organization (ICAO), "About ICAO" (*last accessed* 17 September 2018) ("ICAO works with the Convention's 192 Member States and industry groups to reach consensus on international civil aviation Standards and Recommended Practices (SARPs) and policies in support of a safe, efficient, secure, economically sustainable and environmentally responsible civil aviation sector. These SARPs and policies are used by ICAO Member States to ensure that their local civil aviation operations and regulations conform to global norms, which in turn permits more than 100,000 daily flights in aviation's global network to operate safely and reliably in every region of the world.").

[588] Convention on International Civil Aviation, 7 December 1944, 15 U.N.T.S 295, Arts. 48–55; *see also* International Civil Aviation Organization (ICAO), "How It Works" (*last accessed* 17 September 2018) ("The constitution of ICAO is the Convention on International Civil Aviation, drawn up by a conference in Chicago in November and December 1944, and to which each ICAO Contracting State is a party. According to the terms of the Convention, the Organization is made up of an Assembly, a Council of limited membership with various subordinate bodies and a Secretariat. The chief officers are the President of the Council and the Secretary General. The Assembly, composed of representatives from all Contracting States, is the sovereign body of ICAO. It meets every three years, reviewing in detail the work of the Organization and setting policy for the coming years. It also votes a triennial budget. The Council, the governing body which is elected by the Assembly for a three-year term, is composed of 36 States. The Assembly chooses the Council Member States under three headings: States of chief importance in air transport, States which make the largest contribution to the provision of facilities for air navigation, and States whose designation will ensure that all major areas of the world are represented. As the governing body, the Council gives continuing direction to the work of ICAO. It is in the Council that Standards and Recommended Practices are adopted and incorporated as Annexes to the Convention on International Civil Aviation. The Council is assisted by the Air Navigation Commission (technical matters), the Air Transport Committee (economic matters), the Committee on Joint Support of Air Navigation Services and the Finance Committee. The Secretariat, headed by a Secretary General, is divided into five main divisions: the Air Navigation Bureau, the Air Transport Bureau, the Technical Co-operation Bureau, the Legal Bureau and the Bureau of Administration and Services. In order that the work of the Secretariat reflects a truly international perspective, professional-level personnel are recruited on a broad geographical basis.").

[589] Convention on International Civil Aviation, 7 December 1944, 15 U.N.T.S 295, Art. 65; *see also* International Civil Aviation Organization (ICAO), "How It Works" (*last accessed* 17 September 2018) ("ICAO works in close cooperation with other members of the United Nations family such as the World Meteorological Organization (WMO), the International Telecommunication Union (ITU), the Universal Postal Union (UPU), the World Health

Organization (WHO), the World Tourism Organization (UNWTO) and the International Maritime Organization (IMO).”).

[590] International Civil Aviation Organization (ICAO), “How It Works” (*last accessed* 17 September 2018) (“Non-governmental organizations which also participate in ICAO's work include the Airports Council International (ACI), the Civil Air Navigation Services Organisation (CANSO), the International Air Transport Association (IATA), the International Business Aviation Council (IBAC), International Coordinating Council of Aerospace Industries Associations (ICCAIA), the International Council of Aircraft Owner and Pilot Associations (IAOPA), the International Federation of Air Line Pilots' Associations (IFALPA) and the International Federation of Air Traffic Controllers' Associations (IFATCA).”).

[591] International Civil Aviation Organization (ICAO), “Annual Reports of the Council” (*last accessed* 18 September 2018) (“The Annual Report of the Council of ICAO provides the world aviation community with comprehensive insight into the programmes, activities and achievements of the Organization in support of its mission as defined by the Convention on International Civil Aviation, namely, the safe and orderly development of international civil aviation.”).

[592] International Civil Aviation Organization (ICAO), “Committee on Aviation Environmental Protection (CAEP)” (*last accessed* 17 September 2018) (“The Committee on Aviation Environmental Protection (CAEP) is a technical committee of the ICAO Council established in 1983. CAEP assists the Council in formulating new policies and adopting new Standards and Recommended Practices (SARPs) related to aircraft noise and emissions, and more generally to aviation environmental impact. CAEP undertakes specific studies, as requested by the Council. Its scope of activities encompasses noise, air quality and the basket of measures today considered for reducing international aviation CO_2 emissions, including aircraft technology, operations improvement, market-based measures and alternative fuels. CAEP informs the Council’s and Assembly’s decision making by providing aviation environmental trends assessment including future air traffic projections and impact assessment of proposed policies and developments. The Council reviews and adopts CAEP recommendations, including amendments to the SARPs, and in turn reports to the ICAO Assembly where the main policies on environmental protection are ultimately defined.”).

[593] International Civil Aviation Organization (ICAO) (2016) REPORT OF THE EXECUTIVE COMMITTEE ON AGENDA ITEM 22; *see also* Press Release, ICAO, “Historic agreement reached to mitigate international aviation emissions” (6 October 2016) (“ICAO’s Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) is designed to complement the basket of mitigation measures the air transport community is already pursuing to reduce CO_2emissions from international aviation. These include technical and operational improvements and advances in the production and use of sustainable alternative fuels for aviation. Implementation of the CORSIA will begin with a pilot phase from 2021 through 2023, followed by a first phase, from 2024 through 2026. Participation in both of these early stages will be voluntary and the next phase from 2027 to 2035 would see all States on board. Some exemptions were accepted for Least Developed Countries (LDCs), Small Island Developing States (SIDS), Landlocked Developing Countries (LLDCs) and States with very low levels of international aviation activity.”).

[594] International Civil Aviation Organization (ICAO), “Environmental Protection – Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)” (*last accessed* 18 September 2018) (“In September, ICAO developed draft rules and guidance, including those for a robust Monitoring, Reporting and Verification (MRV) system of CO_2 emissions from international aviation. In November, the Council welcomed the timely delivery of the CAEP recommendations on the CORSIA package, noting that the package consisted of a proposed Volume IV — *CORSIA* of Annex 16 — *Environmental Protection*; a proposed Volume IV of the *Environmental Technical Manual* (Doc 9501); and proposed ICAO CORSIA implementation elements and supporting documents. The proposed Annex 16, Volume IV, and related ICAO CORSIA implementation elements and supporting documents are currently under review by the ICAO process, aiming for adoption by the ICAO Council in June 2018.”).

[595] International Civil Aviation Organization (ICAO), “Environmental Protection – Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)” (*last accessed* 18 September 2018) (“As of 31 December 2017, 72 States, representing 87.7 per cent of international aviation activity, had volunteered to participate in CORSIA from its outset. To ensure the timely implementation of CORSIA, ICAO and its Member States have been prioritizing efforts in undertaking necessary preparatory activities.”).

[596] Arctic Council (1996) DECLARATION ON THE ESTABLISHMENT OF THE ARCTIC COUNCIL; *see also* Arctic Council, "The Arctic Council: a backgrounder" (*last accessed* 15 January 2019) (“The Ottawa Declaration lists the following countries as Members of the Arctic Council: Canada, the Kingdom of Denmark, Finland, Iceland, Norway, the Russian Federation, Sweden and the United States. In addition, six organizations representing Arctic indigenous peoples have status as Permanent Participants. The category of Permanent Participant was created to provide for

active participation and full consultation with the Arctic indigenous peoples within the Council. They include: the Aleut International Association, the Arctic Athabaskan Council, Gwich'in Council International, the Inuit Circumpolar Council, Russian Association of Indigenous Peoples of the North and the Saami Council. Observer status in the Arctic Council is open to non-Arctic states, along with inter-governmental, inter-parliamentary, global, regional and non-governmental organizations that the Council determines can contribute to its work. Arctic Council Observers primarily contribute through their engagement in the Council at the level of Working Groups. The standing Arctic Council Secretariat formally became operational in 2013 in Tromsø, Norway. It was established to provide administrative capacity, institutional memory, enhanced communication and outreach and general support to the activities of the Arctic Council.").

[597] There are presently thirteen non-Arctic observer states: France, Germany, Italy, Japan, The Netherlands, China, Poland, India, South Korea, Singapore, Spain, Switzerland, and United Kingdom. Arctic Council, "Observers" (*last accessed* 11 December 2018).

[598] There are thirteen intergovernmental and inter-parliamentary organizations: International Council for the Exploration of the Sea (ICES), International Federal of Red Cross and Red Crescent Societies (IFRC), International Union for the Conservation of Nature (IUCN), Nordic Council of Ministers (NCM), Nordic Environment Finance Corporation (NEFCO), North Atlantic Marine Mammal Commission (NAMMCO), OSPAR Commission, Standing Committee of the Parliamentarians of the Arctic Region (SCPAR), United Nations Economic Commission for Europe (UN-ECE), United Nations Development Programme (UNDP), United Nations Environment Programme (UNEP), World Meteorological Organization (WMO), and West Nordic Council (WNC). There are also thirteen non-governmental organizations: Advisory Committee on Protection of the Sea (ACOPS), Arctic Institute of North America (AINA), Association of World Reindeer Herders (AWRH), Circumpolar Conservation Union (CCU), International Arctic Science Committee (IASC), International Arctic Social Sciences Association (IASSA), International Union for Circumpolar Health (IUCH), International Work Group for Indigenous Affairs (IWGIA), National Geographic Society (NGS), Northern Forum (NF), Oceana, University of the Arctic (UArctic), and World Wide Fund for Nature-Global Arctic Program (WWF). Arctic Council, "Observers" (*last accessed* 11 December 2018).

[599] Arctic Council, "Observers" (*last accessed* 11 December 2018).

[600] Arctic Council, "The Arctic Council: a backgrounder" (*last accessed* 16 April 2018) ("The Arctic Council regularly produces comprehensive, cutting-edge environmental, ecological and social assessments through its Working Groups. Click here to see a list of some significant products from the Working Groups. The Council has also provided a forum for the negotiation of three important legally binding agreements among the eight Arctic States. The first, the Agreement on Cooperation on Aeronautical and Maritime Search and Rescue in the Arctic, was signed in Nuuk, Greenland, at the 2011 Ministerial Meeting. The second, the Agreement on Cooperation on Marine Oil Pollution Preparedness and Response in the Arctic, was signed in Kiruna, Sweden, at the 2013 Ministerial meeting. The third, the Agreement on Enhancing International Arctic Scientific Cooperation, was signed in Fairbanks, Alaska at the 2017 Ministerial meeting.").

[601] Arctic Council, "The Arctic Council: a backgrounder" (*last accessed* 16 April 2018) ("The Arctic Council is a forum; it has no programming budget. All projects or initiatives are sponsored by one or more Arctic States. Some projects also receive support from other entities. The Arctic Council does not and cannot implement or enforce its guidelines, assessments or recommendations. That responsibility belongs to each individual Arctic State. The Arctic Council's mandate, as articulated in the Ottawa Declaration, explicitly excludes military security.").

[602] Arctic Council Secretariat (2017) EXPERT GROUP ON BLACK CARBON AND METHANE: SUMMARY OF PROGRESS AND RECOMMENDATIONS 2017, 4 ("All eight Arctic States and five Observer States (France, India, Italy, Spain and the United Kingdom) developed and submitted inventories of black carbon and methane emissions, as well as methane projections. Six out of eight Arctic States provided black carbon projections, along with the United Kingdom. For some countries, black carbon emission inventories or projections were developed for the first time in fulfillment of the commitment to do so under the Framework, a foundational step in the Framework's implementation.").

[603] Arctic Monitoring and Assessment Programme (AMAP) (2015) AMAP ASSESSMENT 2015: BLACK CARBON AND OZONE AS ARCTIC CLIMATE FORCERS, 30 ("This section focuses on two emission source sectors: Arctic shipping and flaring in the Arctic oil and gas industries (e.g. Corbett et al. 2010; Peters et al. 2011; Stohl et al. 2013; Winther et al. 2014). Characteristic for both sources are that the emissions occur at high latitudes and that activities in the Arctic associated with these sources may increase significantly in the future.").

[604] Arctic Monitoring and Assessment Programme (AMAP) (2015) AMAP ASSESSMENT 2015: BLACK CARBON AND OZONE AS ARCTIC CLIMATE FORCERS, 31 ("In the Business-as-Usual scenario, emissions are estimated to roughly

double by 2030 relative to the base year (see Figs. 5.10 and 5.11). Most of the increase in shipping activity and emissions is due to the shift in global traffic away from the traditional routes into Arctic waters. In addition, traffic along routes within the Arctic area is expected to increase (Corbett et al. 2010; Peters et al. 2011; Winther et al. 2014). By 2050 in the Business-as-Usual scenario, C2010 projects a further doubling of emissions compared with 2030, while P2011 projects an approximate 1.3-fold increase (Fig. 5.11). W2014 projects emissions increases that fall between the two.").

[605] Arctic Council Secretariat (2017) EXPERT GROUP ON BLACK CARBON AND METHANE: SUMMARY OF PROGRESS AND RECOMMENDATIONS 2017, 17 ("Arctic shipping currently accounts for about 5 percent of black carbon emissions within the Arctic; absent emission controls, shipping emissions within the Arctic could double by 2030 under some projections of Arctic vessel traffic. In response to concerns over air quality and human health impacts associated with shipping emissions, a number of relevant actions have been undertaken, such as: The establishment through the IMO of Emission Control Areas where the adoption of special mandatory measures for emissions from ships limits nitrogen oxide emissions, sulphur oxide emissions, or both; Agreement under the IMO to a global sulphur cap of 0.5 percent for fuel to be implemented starting 1 January 2020; Incentivizing the uptake of emission abatement technologies, electrification of ports, fuel efficiency improvements, or use of alternative fuels; Engaging in ongoing work within the IMO's Sub-Committee on Pollution Prevention and Response (PPR) to identify appropriate methods for measuring black carbon emissions from international shipping and to consider possible control measures; and Participating in the Arctic Council's Working Group on the Protection of the Arctic Marine Environment (PAME) and its Shipping Experts Group.").

[606] Arctic Council Secretariat (2017) EXPERT GROUP ON BLACK CARBON AND METHANE: SUMMARY OF PROGRESS AND RECOMMENDATIONS 2017, 4 ("Black carbon inventories submitted by Arctic States (which generally did not include wildfire or open burning emission sources) indicate that diesel engines are the largest source followed by residential emissions from biomass combustion. Although black carbon emissions from oil and gas flaring are not reported by all Arctic States, the Arctic Council's Arctic Monitoring and Assessment Programme (AMAP) has indicated that flaring is the second largest source of black carbon emissions from Arctic States, mainly due to Russian Federation emissions. Most but not all Arctic States submitted projections. Assuming no change in emissions by those Arctic States that did not submit projections, black carbon emissions across Arctic States are collectively projected to decrease by 24 percent from 2013 levels by 2025. This decrease is due mainly to standards for new vehicle engines and retirement of older, higher-emitting vehicles. Significantly, many Arctic countries substantially cut their emissions of black carbon prior to 2013, and these reductions are already reflected in the baseline for the current projections.").

[607] Arctic Council, "About ACAP" (*last accessed* 16 April 2018) ("ACAP was originally founded as an Arctic Council plan to address the Arctic pollution sources identified through AMAP. It became Arctic Council's sixth permanent Working Group in 2006. It acts as a strengthening and supporting mechanism to encourage national actions to reduce emissions and other releases of pollutants. Co-operative actions will make an important and significant contribution to the overall international effort to reduce environmental damage on a global level.").

[608] Arctic Council, "ACAP Expert Group on Short-Lived Climate Pollutants (SLCP)" (*last accessed* 16 April 2018).

[609] Council of the European Union (2017) COUNCIL DECISION (EU) 2017/1757 OF 17 JULY 2017 ON THE ACCEPTANCE ON BEHALF OF THE EUROPEAN UNION OF AN AMENDMENT TO THE 1999 PROTOCOL TO THE 1979 CONVENTION ON LONG-RANGE TRANSBOUNDARY AIR POLLUTION TO ABATE ACIDIFICATION, EUTROPHICATION AND GROUND-LEVEL OZONE.

[610] Council of the European Union (2016) DIRECTIVE (EU) 2016/2284 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL OF 14 DECEMBER 2016 ON THE REDUCTION OF NATIONAL EMISSIONS OF CERTAIN ATMOSPHERIC POLLUTANTS, AMENDING DIRECTIVE 2003/35/EC AND REPEALING DIRECTIVE 2001/81/EC. Directive 2001/81/EC focused on ground-level ozone and avoiding emissions of its precursors, requiring national emissions ceilings by 2010 and increased by 2020. Council of the European Union (2001) DIRECTIVE 2001/81/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL OF 23 OCTOBER 2001 ON NATIONAL EMISSION CEILINGS FOR CERTAIN ATMOSPHERIC POLLUTANTS, Article 1 ("The aim of this Directive is to limit emissions of acidifying and eutrophying pollutants and ozone precursors in order to improve the protection in the Community of the environment and human health against risks of adverse effects from acidification, soil eutrophication and ground-level ozone and to move towards the long-term objectives of not exceeding critical levels and loads and of effective protection of all people against recognised health risks from air pollution by establishing national emission ceilings, taking the years 2010 and 2020 as benchmarks, and by means of successive reviews as set out in Articles 4 and 10.").

[611] Swedish Environmental Protection Agency (2017) REPORT FOR SWEDEN ON ASSESSMENT OF PROJECTED PROGRESS, MARCH 2017, 11 ("Petrol and diesel are covered by both an energy tax and a carbon dioxide tax. In

accordance with the climate policy decision in 2009, the energy tax on diesel has been raised in two stages, in 2011 and 2013, by a total of SEK 0.40 per liter8. As of January 2016 the energy tax on diesel was increased by another SEK 0.52 per liter and on petrol by SEK 0.47 per liter.9 From 2017, and each year onwards, the energy and carbon dioxide tax will be adjusted upwards with 2 percent. The taxes are also adjusted with the rate of inflation (Swedish consumer price index).").

[612] Ministerie van Infrastructuur en Milieu (2017) NETHERLANDS NATIONAL REPORT ON BLACK CARBON AND METHANE EMISSIONS, 8 ("Nevertheless, BC emissions from road transport have decreased by 83% between 1990 and 2015. This decrease can mainly be attributed to the introduction of increasingly stringent European emission standards for new road vehicles. For example, diesel particulate filters (DPFs) are required to comply with the Euro 5 PM emission standard, which entered into force at the start of 2011. DPFs entered the Dutch market much earlier though, helped by a subsidy that was instated by the Dutch government in 2005. In 2007, more than 60% of new diesel passenger cars was already equipped with a DPF. Since 2008, the share of new diesel passenger cars with a DPF has been above 90%.").

[613] Ministerie van Infrastructuur en Milieu (2017) NETHERLANDS NATIONAL REPORT ON BLACK CARBON AND METHANE EMISSIONS, 9 ("According to the Environmental Management Act (Wet Milieubeheer), the Minister of Infrastructure and the Environment (I&M) must issue a Waste Management Plan once every six years. The National Waste Management Plan 2002-2012 (Landelijk Afvalbeheerplan 2002–2012) was the first such plan. It was replaced in 2009 by a new plan for the period 2009–2021. The policy aims to minimise the production of waste, to maximise recycling and other recovery, and to minimise the amount of waste that remains for disposal, especially landfill. An important target of the waste policy is to increase overall recycling from 79% (in 2008) to 83% (in 2015). In order to achieve this target, the focus has been on the separating of household waste for collection, because almost 50% of this waste flow is still incinerated. Non-recyclable waste is incinerated in energy-efficient incinerators, which are all designated as installations for other recovery in accordance with the Waste Framework Directive. Optimisation of waste management makes an important contribution to the mitigation of the greenhouse effect. Landfill of organic waste, for example, generates substantial methane emissions. This is one of the reasons why the waste policy focuses on maximising waste recycling and limiting waste disposal. In 2010, around 2% of waste produced in the Netherlands was sent to landfill. This waste could not be recycled or burned. … Voluntary agreements with the oil, gas and aluminum industries to improve their energy efficiency has resulted in reductions in CH_4 emissions.").

[614] Ministerie van Infrastructuur en Milieu (2017) NETHERLANDS NATIONAL REPORT ON BLACK CARBON AND METHANE EMISSIONS, 11 ("The Netherlands Polar Programme is one of the cornerstones of the Dutch Polar Strategy 2016–2020. NWO, The Netherlands Organisation for Scientific Reserach, coordinates the implementation of this programme and funds scientific research into and in the polar regions. The programme has four priority areas: ice, climate and sea level rise; polar ecosystems; sustainable exploitation; and social, juridical and economic issues.").

[615] California Global Warming Solutions Act of 2006, A.B. 32, 2005–2007 Leg. (Cal. 2006) ("This bill would require the state board to adopt regulations to require the reporting and verification of statewide greenhouse gas emissions and to monitor and enforce compliance with this program, as specified. The bill would require the state board to adopt a statewide greenhouse gas emissions limit equivalent to the statewide greenhouse gas emissions levels in 1990 to be achieved by 2020, as specified. The bill would require the state board to adopt rules and regulations in an open public process to achieve the maximum technologically feasible and cost-effective greenhouse gas emission reductions, as specified. The bill would authorize the state board to adopt market-based compliance mechanisms, as defined, meeting specified requirements. The bill would require the state board to monitor compliance with and enforce any rule, regulation, order, emission limitation, emissions reduction measure, or market-based compliance mechanism adopted by the state board, pursuant to specified provisions of existing law. The bill would authorize the state board to adopt a schedule of fees to be paid by regulated sources of greenhouse gas emissions, as specified.").

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

[617] S.B. 1013, 2017–2018 Leg. (Cal. 2018).

[618] Under2 MOU, "Background" (*last accessed* 16 April 2018) ("The Under2 Coalition is a global community of ambitious sub-national governments publicly committed to long-term deep decarbonization and supporting the Paris Agreement's climate goal of keeping the rise in global average temperature well below 2°C. The Coalition brings together signatories of the Under2 MOU (Memorandum of Understanding), a commitment by governments to limit their greenhouse gas emissions by 80 to 95% below 1990 levels, or to 2 annual metric tons of carbon dioxide-equivalent per capita, by 2050. The Under2 Coalition is an initiative primarily driven by state, regional and provincial governments. However, jurisdictions at all levels of government are encouraged to sign or endorse the Under2 MOU, thus committing to deep decarbonization in their jurisdictions. Signatories include over 200 states, provinces, regions and cities, as well as national government endorsers. Together they represent almost 40 percent of the global economy. The Climate Group acts as the Secretariat for the Coalition.").

[619] Under2 MOU, "Background" (*last accessed* 16 April 2018) ("The Under2 Coalition is a global community of ambitious sub-national governments publicly committed to long-term deep decarbonization and supporting the Paris Agreement's climate goal of keeping the rise in global average temperature well below 2°C. The Coalition brings together signatories of the Under2 MOU (Memorandum of Understanding), a commitment by governments to limit their greenhouse gas emissions by 80 to 95% below 1990 levels, or to 2 annual metric tons of carbon dioxide-equivalent per capita, by 2050. The Under2 Coalition is an initiative primarily driven by state, regional and provincial governments. However, jurisdictions at all levels of government are encouraged to sign or endorse the Under2 MOU, thus committing to deep decarbonization in their jurisdictions. Signatories include over 200 states, provinces, regions and cities, as well as national government endorsers. Together they represent almost 40 percent of the global economy. The Climate Group acts as the Secretariat for the Coalition.").

[620] U.S. Climate Alliance, "About: Alliance Principles" (*last accessed* 5 June 2018) ("In response to the U.S. federal government's decision to withdraw the United States from the Paris Agreement, Governors Andrew Cuomo, Jay Inslee, and Jerry Brown launched the United States Climate Alliance – a bipartisan coalition of governors committed to reducing greenhouse gas emissions consistent with the goals of the Paris Agreement. Smart, coordinated state action can ensure that the United States continues to contribute to the global effort to address climate change. The Alliance has three core principles: States are continuing to lead on climate change: Alliance states recognize that climate change presents a serious threat to the environment and our residents, communities, and economy. State-level climate action is benefiting our economies and strengthening our communities: Alliance members are growing our clean energy economies and creating new jobs, while reducing air pollution, improving public health, and building more resilient communities. States are showing the nation and the world that ambitious climate action is achievable: Despite the U.S. federal government's decision to withdraw from the Paris Agreement, Alliance members are committed to supporting the international agreement, and are pursuing aggressive climate action to make progress toward its goals.").

[621] U.S. Climate Alliance, "About: Alliance Principles" (*last accessed* 5 June 2018) ("Each member state commits to: Implement policies that advance the goals of the Paris Agreement, aiming to reduce greenhouse gas emission by at least 26-28 percent below 2005 levels by 2025, track and report progress to the global community in appropriate settings, including when the world convenes to take stock of the Paris Agreement, and accelerate new and existing policies to reduce carbon pollution and promote clean energy deployment at the state and federal level.").

[622] U.S. Climate Alliance, "Short-Lived Climate Pollutant Challenge" (*last accessed* 5 June 2018) ("Reducing emissions of potent short-lived climate pollutants provides outsized global climate benefits in the near-term, along with significant health, agricultural, and ecosystem benefits. Targeted commitments and strategies to rapidly and significantly reduce these pollutants, which include methane, hydrofluorocarbons (HFCs) and black carbon, will minimize the risks of climate change and maximize local benefits associated with addressing it. Immediate action on these pollutants is necessary to limit the global temperature increase to well below 2°C, and to pursue efforts to limit the increase to 1.5°C. On June 1, 2018, the U.S. Climate Alliance committed to reducing short-lived climate pollutants as a critical component to meeting the goals of the Paris Agreement. The Alliance invites all national and subnational jurisdictions, businesses and other actors to bring commitments to reduce short-lived climate pollutants to the Global Climate Action Summit in San Francisco, California this September.").

[623] U.S. Climate Alliance, "Short-Lived Climate Pollutant Challenge" (*last accessed* 5 June 2018) ("On June 1, 2018, the U.S. Climate Alliance committed to reducing short-lived climate pollutants as a critical component to meeting the goals of the Paris Agreement. The Alliance invites all national and subnational jurisdictions, businesses and other actors to bring commitments to reduce short-lived climate pollutants to the Global Climate Action Summit in San Francisco, California this September. In the coming months, the Alliance will work to comprehensively address short-lived climate pollutants, including through new and continued actions to improve emissions inventories; quickly identify and address methane leaks and "super emitters;" promote energy efficiency, including

in refrigeration and cooling; phasedown the use of HFCs; improve management of organic and agricultural waste streams; and define other targets and measures to rapidly reduce emissions of these potent pollutants.").

624 United Nations, "Sustainable Development Knowledge Platform" (*last accessed* 29 May 2018).

625 Haines A., *et al.* (2017) *Short-lived climate pollutant mitigation and the Sustainable Development Goals*, NATURE CLIMATE CHANGE 7:863–869, 868 ("Implementing SLCP mitigation measures can contribute to the achievement of multiple SDG targets. As countries seek to incorporate SDG implementation into their national policy and planning processes, it is important that multiple benefits are assessed to identify actions and strategies that can help achieve several SDG targets, while minimizing conflicts and trade-offs. For most SLCP measures, there are synergies, often between many different SDGs and their targets. SLCP mitigation is complementary to CO_2 mitigation; many SLCP mitigation strategies can yield CO_2 mitigation co-benefits and vice versa.").

626 Haines A., *et al.* (2017) *Short-lived climate pollutant mitigation and the Sustainable Development Goals*, NATURE CLIMATE CHANGE 7:863–869.

627 Haines A., *et al.* (2017) *Short-lived climate pollutant mitigation and the Sustainable Development Goals*, NATURE CLIMATE CHANGE 7:863–869.

628 Haines A., *et al.* (2017) *Short-lived climate pollutant mitigation and the Sustainable Development Goals*, NATURE CLIMATE CHANGE 7:863–869.

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