

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

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

**Background Note**

**DRAFT: 15 February 2021**



Institute for Governance  
& Sustainable Development (IGSD)



Center for Human Rights and  
Environment (CHRE/CEDHA)

## About the Institute for Governance & Sustainable Development (IGSD)

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

As part of its work, IGSD is pursuing “fast-action” climate mitigation strategies that will result in significant reductions of climate emissions to limit temperature increase and other climate impacts in the near-term. The focus is on strategies to reduce non-CO<sub>2</sub> climate pollutants, protect sinks, and enhance urban albedo with smart surfaces, as a complement to cuts in CO<sub>2</sub>. It is essential to reduce both non-CO<sub>2</sub> pollutants and CO<sub>2</sub>, as neither alone is sufficient to provide a safe climate.

IGSD's fast-action strategies include reducing emissions of the short-lived climate pollutants—black carbon, methane, tropospheric ozone, and hydrofluorocarbons (HFCs). Reducing HFCs starting with the Kigali Amendment to the Montreal Protocol has the potential to avoid up to 0.5°C of warming by end of century. Parallel efforts to enhance energy efficiency of air conditioners and other cooling appliances during the phase down of HFCs can double the climate benefits at 2050, and by [2060 avoid the equivalent of up to 460 billion tonnes of CO<sub>2</sub>](#).

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

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

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



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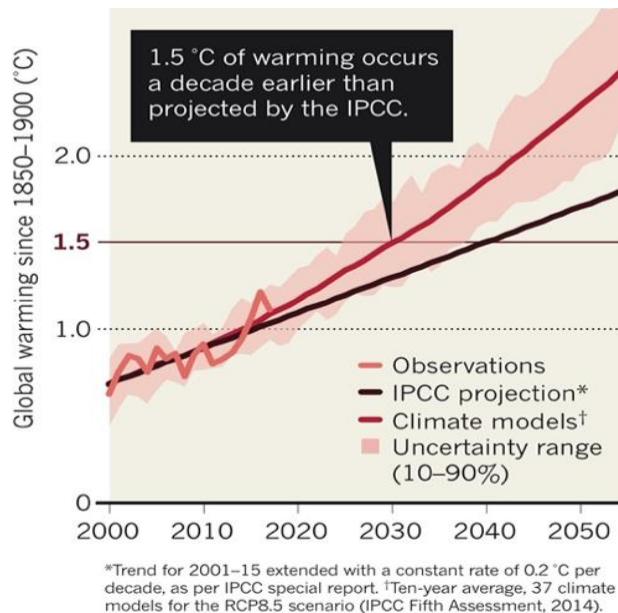
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## 1. Introduction and summary

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

- Along the way to achieving the 2050 Net Zero target—or better, a Real Zero target—it is critical to select a pathway that not only reduces CO<sub>2</sub> but that also reduces the short-lived climate pollutants (SLCPs)—black carbon, methane, tropospheric ozone, and HFC refrigerants—as fast as possible, along with other fast mitigation strategies, including [protection of sinks](#); this is [essential for achieving near-term and long-term climate targets](#), including the 2050 Net Zero target. (SLCPs are often referred to as “super pollutants” because of their potency.)
- [Speed must become a key goal for selecting climate solutions](#),<sup>1</sup> in order to provide the most avoided warming in the shortest period of time over the next decade or two, to slow the self-reinforcing [feedbacks and avoid tipping points](#),<sup>2</sup> and to protect the most [vulnerable people and ecosystems](#).<sup>3</sup>
- The window for effective mitigation to slow feedbacks and avoid tipping points is shrinking to perhaps 10 years or less,<sup>4</sup> including the window to prevent [crashing through the 1.5 °C guardrail](#).<sup>5</sup>

**Figure 1: Projected warming**



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

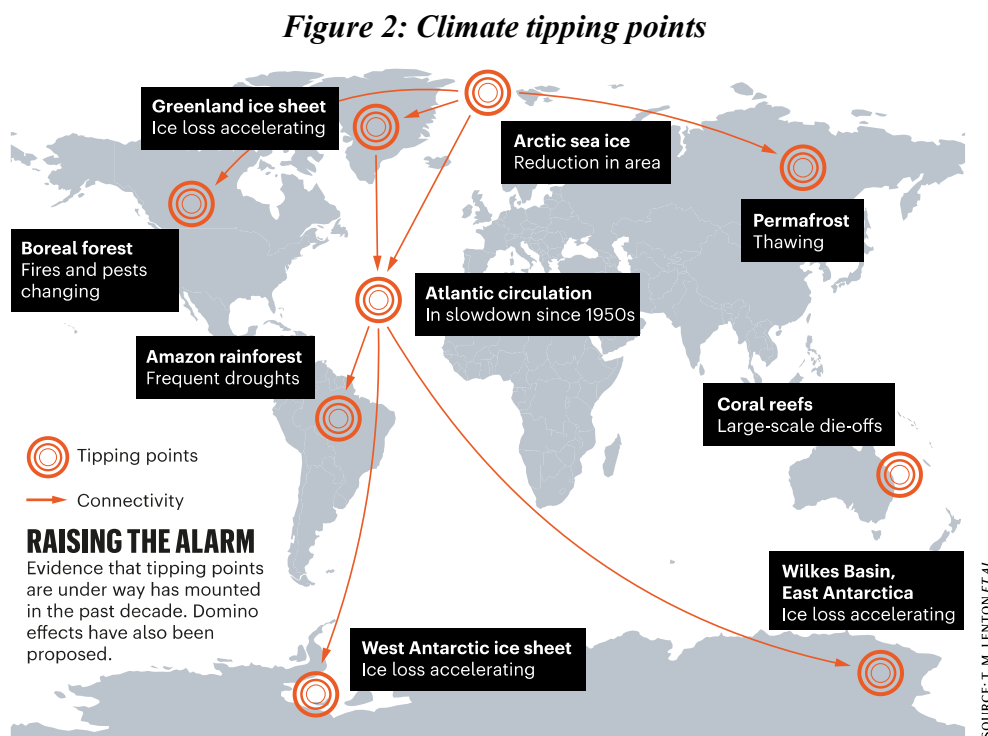
- The world could hit the 1.5 °C guardrail by 2030, due to rising emissions, declining particulate air pollution that un masks existing warming, and natural climate variability.<sup>6</sup>
- In the five years between 2020–2024, the annual global temperature is expected to be at least 1 °C warmer than the 1850–1900 average (range of 0.91–1.59 °C), with a one-in-four chance that at least one year could be 1.5 °C warmer, even if only temporarily, according to the World Meteorological Organization.<sup>7</sup>

- The three strategies that are essential for keeping the planet safe are: (i) reducing CO<sub>2</sub>, (ii) reducing short-lived super climate pollutants (SLCPs or super climate pollutants), and (iii) removing up to 1,000 billion tons of CO<sub>2</sub> from the atmosphere by 2100, according to the IPCC's Special Report on 1.5 °C.<sup>8</sup>
- Cutting the SLCPs can avoid three times more warming at 2050 than CO<sub>2</sub> cuts,<sup>9</sup> [reducing projected warming in the Arctic by two-thirds and the rate of global warming by half.](#)<sup>10</sup>

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

Evidence from feedbacks and tipping points suggests that we are already in a state of planetary emergency, where both the risk and urgency of the emergency are acute. Six tipping points are projected to occur between the current 1 °C of warming and the 1.5 °C of warming expected in the next 10 years, with another 11 tipping points projected between 1.5 °C and 2 °C.<sup>11</sup>

- Self-reinforcing feedbacks, including the loss of Arctic sea ice, are among the [most vulnerable links in the chain of climate protection.](#)<sup>12</sup>



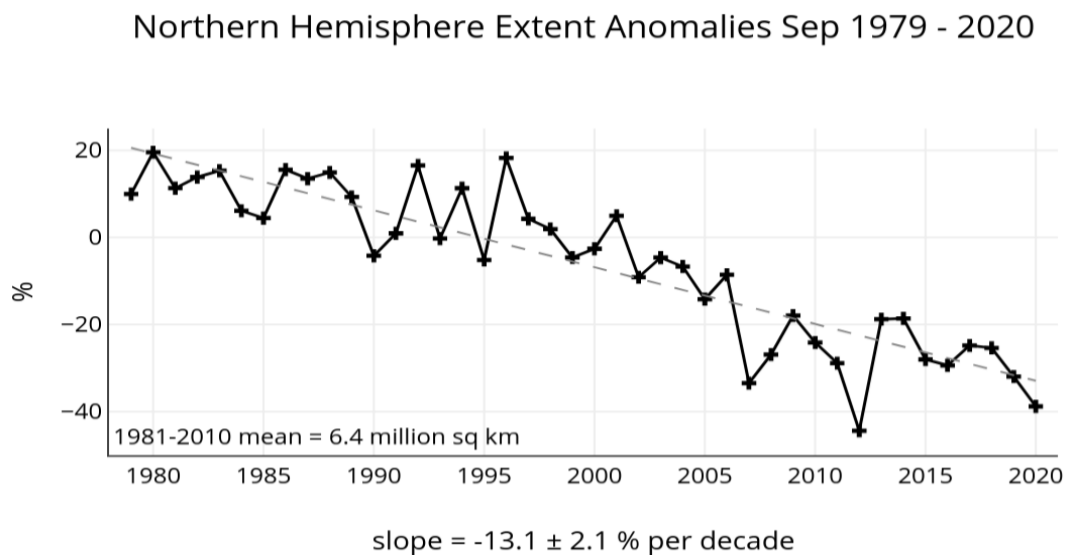
Source: Lenton T. M., Rockstrom J., Gaffney O., Rahmstorf S., Richardson K., Steffen W., & Schellnhuber H. J. (2019) [Climate tipping points—too risky to bet against](#), NATURE, Comment, 575(7784):592–595.

## 3. Shrinking Arctic shield

Over the past several decades the Arctic air temperature has been warming at three times the global average according to NOAA and NASA,<sup>13</sup> and up to four times the global average for the area above 70°N,<sup>14</sup> with even greater warming over the Arctic ocean.<sup>15</sup> As a result, the extent of Arctic sea ice—a white shield reflecting incoming solar radiating safely back to space—is shrinking.<sup>16</sup>

- From 1994 to 2017, the Arctic lost 7.6 trillion tons of sea ice, contributing to over a quarter of global ice loss in that period.<sup>17</sup>
  - “The rate of [global] ice loss has risen by 57 % since the 1990s – from 0.8 to 1.2 trillion tonnes per year.... Even though Earth's cryosphere has absorbed only a small fraction of the global energy imbalance [ $3.2 \pm 0.3\%$ ] it has lost a staggering 28 trillion tonnes of ice between 1994 and 2017.... [T]here can be little doubt that the vast majority of Earth's ice loss is a direct consequence of climate warming.”<sup>18</sup>
- “The Arctic is rapidly warming and experiencing tremendous changes in sea ice....<sup>19</sup>
  - The 14 Septembers with the least Arctic sea ice extent have all been in the last 14 years; on September 15, 2020, the Arctic sea ice reached its annual minimum as the second lowest extent in the satellite record.<sup>20</sup>
  - Through late October 2020, the Arctic sea ice had not yet begun freezing in the Laptev Sea, an area known as the “birthplace of ice” for the Arctic Ocean.<sup>21</sup>
- The Arctic could become nearly ice-free in late summer during the September minimum extent within a decade or two, further reducing its heat-reflecting ability.<sup>22</sup>
  - Conditions free of sea ice over multiple summer months likely occurred during the last interglacial period, providing further independent support for predictions of ice-free conditions in late summer by 2035.<sup>23</sup>
  - Arctic summer sea ice in the seas surrounding the central Arctic Ocean—the “shelf seas”—will likely vanish during the late summer shortly after mid-century, with the Barents Sea seeing ice-free conditions in winter before the end of the century.<sup>24</sup>

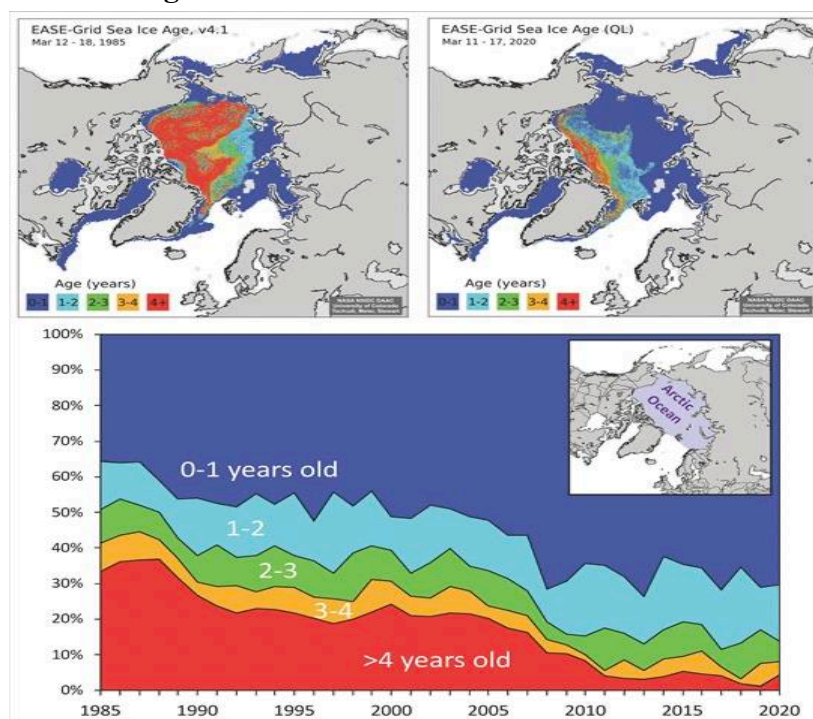
**Figure 3: Monthly sea ice extent anomalies**



Graph” (last accessed 6 October 2020) (“This graph shows monthly ice extent anomalies plotted as a time series of percent difference between the extent for the month in question and the mean for that month based on the January 1981 to December 2010 data. The anomaly data points are plotted as plus signs and the trend line is plotted with a dashed grey line.”).

- In the extreme case when all Arctic sea ice is lost for all sunlit months, climate forcing [equivalent to one trillion tons of CO<sub>2</sub>](#) would be added to the climate system—on top of the forcing from the 2.4 trillion tons of CO<sub>2</sub> added in the 270 years since the Industrial Revolution—, and this would advance warming by 25 years.<sup>25</sup>
  - This additional warming would be the equivalent of adding 56 ppm of CO<sub>2</sub><sup>26</sup> to the current CO<sub>2</sub> concentration, which reached a seasonal peak of 417 ppm in May 2020.<sup>27</sup>
  - The added forcing in the Arctic would be 21 W/m<sup>2</sup>; averaged globally would equal 0.71 W/m<sup>2</sup> of global forcing,<sup>28</sup> compared to the [1.83 W/m<sup>2</sup> added by anthropogenic emissions of CO<sub>2</sub> since the Industrial Revolution](#).<sup>29</sup>
- If all of the cloud cover over the Arctic dissipates along with the loss of all sea ice, the added Arctic warming could be three times as much—the equivalent of three trillion tons of CO<sub>2</sub>; in contrast, if clouds increase to create completely overcast skies over the Arctic, the warming would still add the equivalent of 500 billion tons of CO<sub>2</sub> to the atmosphere.<sup>30</sup>
- Further jeopardizing the future of summer sea ice is the loss of the strong, very old (>4 years old) multi-year Arctic sea ice, which comprised only 4.4% of the Arctic Ocean in March 2020; young, first-year ice—which is thinner, more fragile, and more susceptible to decline—now comprises most of the ice pack.<sup>31</sup>
  - Less sea ice in the Arctic Ocean allows ocean waves to grow larger, allowing for an acceleration of ice breakup and retreat.<sup>32</sup> Arctic warming also leads to a greater number of cyclones and to more intense cyclones,<sup>33</sup> which contribute to Arctic sea ice decline.<sup>34</sup>
  - Declining Arctic sea ice has created an environment where more of the warmer Atlantic Ocean water enters the Arctic Ocean, which can further reduce sea ice thickness.<sup>35</sup>

**Figure 4: Late Winter Sea Ice in Arctic**



Source: Perovich D., Meier W., Tschudi M., Hendricks S., Petty A. A., Divine D., Farrell S., Gerlan S., Haas C., Kaleschke L., Pavlova O., Ricker R., Tian-Kunze X., Webster M., & Wood K. (2020) [Sea Ice](#), in [ARCTIC REPORT CARD 2020](#), Thoman R. L., Richter-Menge J., & Druckenmiller M. L. (eds.), National Oceanic and Atmospheric Administration (NOAA), 49 (“Fig. 3. Late winter sea ice age coverage map for the week of 12-18 March 1985 (upper left) and 11-17 March 2020 (upper right). Bottom: Sea ice age percentage within the Arctic Ocean for the week of 11-18 March 1985-2020. Data are from NSIDC (Tschudi et al. 2019, 2020).”).

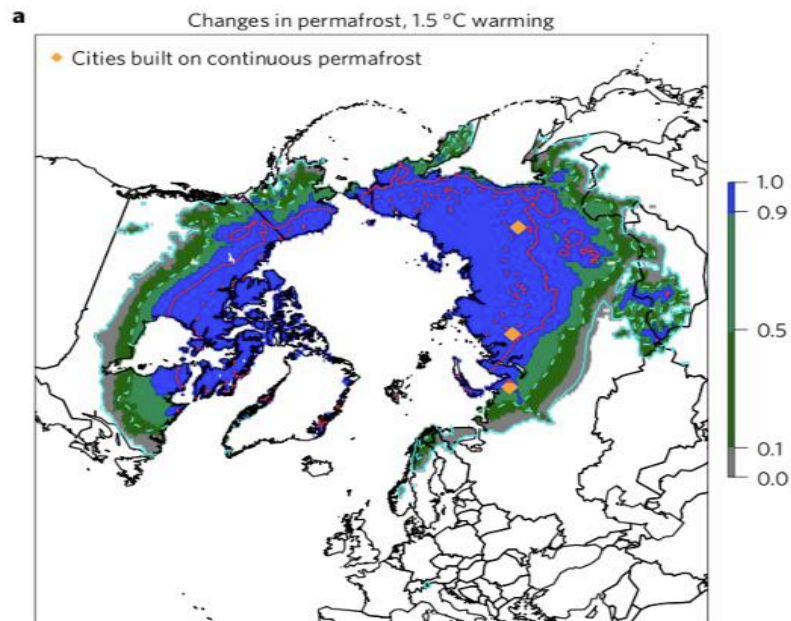


#### 4. Permafrost emissions of CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O

The accelerated Arctic warming [risks triggering another self-reinforcing feedback—permafrost thaw](#)<sup>36</sup>—which would further [amplify warming by releasing CO<sub>2</sub> and methane \(CH<sub>4</sub>\)](#),<sup>37</sup> as well as [nitrous oxide \(N<sub>2</sub>O\), which also destroys stratospheric ozone](#).<sup>38</sup>

- Of the approximately 15 million square kilometers of permafrost,<sup>39</sup> 3.4 million square kilometers have already thawed; and with warming of 1.5 °C approaching, [another 4.8 million square kilometers could thaw](#).<sup>40</sup>
  - Abrupt thaw “will probably occur in <20% of the permafrost zone but could affect half of permafrost carbon,” and “models considering only gradual permafrost thaw are substantially underestimating carbon emissions.”<sup>41</sup>
  - The amount of carbon stored in permafrost is nearly twice what is already in the atmosphere—[1,700 Gt carbon in permafrost versus 850 Gt carbon in the atmosphere](#).<sup>42</sup>

**Figure 4: Changes in permafrost**



Source: Chadburn S. E., Burke E. J., Cox P. M., Friedlingstein P., Hugelius G., & Westermann S. (2017) [An observation-based constraint on permafrost loss as a function of global warming](#), NAT. CLIM. CHANGE 7(5):340–344 (“Figure 4 | Changes in spatial patterns of permafrost under future stabilization scenarios. a,b, The shaded areas show estimated historical permafrost distribution (1960–1990), and contours show the plausible range of zonal boundaries under 1.5 C stabilization (a) and under 2 C stabilization (b).”).

- Reduced Arctic snow cover leads to increased risk of black carbon-emitting wildfires<sup>43</sup>, and drier surfaces combined with fires and thawing can increase carbon emissions 40%.<sup>44</sup>

## 5. Methane from Arctic Shelf

There also is a risk—though probably unlikely—that methane will be emitted from the shallow seabed of the East Siberian Arctic Shelf as the Arctic ocean warms,<sup>45</sup> which would speed up other global warming impacts.<sup>46</sup>

- Measurements in October 2020 by [an international expedition](#) on board a Russian research vessel are showing elevated methane release from the Arctic Shelf, according to a story by Jonathan Watts in *The Guardian*, '[Sleeping giant' Arctic methane deposits starting to release, scientists find](#) (27 October 2020). The story quotes Swedish scientist Örjan Gustafsson of Stockholm University, stating that the “East Siberian slope methane hydrate system has been perturbed and the process will be ongoing.”
- According to an earlier isotopic analysis of methane from an Antarctic ice core record, up to 27% of methane emissions during the last deglaciation may have come from old carbon reservoirs of permafrost and hydrates; while this “serves only as a partial analog to current anthropogenic warming,” the authors stated that it is “unlikely” that today’s anthropogenic warming will release the carbon in these old reservoirs.<sup>47</sup>

## 6. Increasing melt rate of Greenland Ice Sheet

[Other tipping points and feedbacks exist between 1.5 °C and 2 °C](#),<sup>48</sup> as confirmed by two of the most recent IPCC Special Reports [from October 2018](#)<sup>49</sup> and [September 2019](#).<sup>50</sup>

- Currently, the best estimate of the threshold for irreversible melting of the Greenland Ice Sheet is 1.6 °C; and while it may take several millennia to see the full extent of the sea-level rise—which would contribute 5–7 meters if all of Greenland melted—the “timescale of melt depends strongly on the magnitude and duration of the temperature overshoot.”<sup>51</sup>
  - In the past two decades, the melt rate across Greenland increased 250–575%<sup>52</sup> and the ice discharge from the Greenland Ice Sheet substantially increased; this will likely persist in the coming years.<sup>53</sup>
- The “evidence from tipping points alone suggests that we are in a state of planetary emergency: both the risk and urgency of the situation are acute....”<sup>54</sup>

## 7. Persistence of ocean warming

Compounding the risk from self-reinforcing feedbacks and tipping points, warming will continue well after emissions stop; [about 93% of the energy imbalance accumulates in the oceans](#) as increased heat,<sup>55</sup> and this [will return to the atmosphere on a timescale of decades to centuries](#) after emissions stop.<sup>56</sup>

## 8. Limited role of CO<sub>2</sub> mitigation for near-term cooling

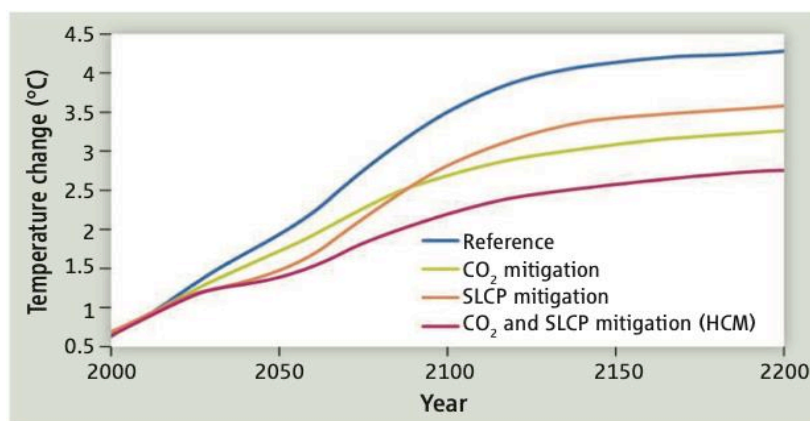
Cutting CO<sub>2</sub> emissions by shifting from fossil fuels to clean energy is essential to do as fast as possible, but doing so will reduce co-emitted cooling aerosols along with CO<sub>2</sub>, offsetting climate benefits and even producing initial warming over the first decade or more.<sup>57</sup>

- These reflective particles are emitted during combustion of fossil fuels and currently “mask” warming of about 0.51 °C; and while the accumulated CO<sub>2</sub> in the atmosphere will continue to

cause warming for decades to centuries, the cooling aerosols will fall out of the atmosphere within days to months un-masking more of the existing warming.<sup>58</sup>

- Fast cuts to CO<sub>2</sub> could avoid 0.1 °C of warming by 2050 and up to 1.6 °C by 2100,<sup>59</sup> not accounting for warming due to the unmasking.<sup>60</sup>
  - This would require CO<sub>2</sub> emissions to peak in 2030 and decline by 5.5% per year until carbon neutrality is reached around 2060–2070, after which emissions level off.<sup>61</sup>
  - If CO<sub>2</sub> emissions were to peak in 2020 (this year) and decline at 5.5% per year until carbon neutrality is reached around mid-century then level off, this extreme scenario could avoid 0.3 °C of warming by 2050 and up to 1.9 °C by 2100, although unmasking of the cooling aerosol would still lead to net warming in the near term.<sup>62</sup>
  - A separate study found near-term warming within the next two decades of 0.02–0.1 °C due to cuts to fossil fuel CO<sub>2</sub> emissions and associated reductions in cooling aerosols.<sup>63</sup>

**Figure 5: Climate temperature response to reductions in emissions of CO<sub>2</sub>, SLCPs, or both**



Source: Shoemaker J. K., Schrag D. P., Molina M. J., & Ramanathan V. (2013) *What Role for Short-Lived Climate Pollutants in Mitigation Policy?*, SCIENCE 342(6164):1323–1324.

## 9. Maximum role for mitigating short-lived super climate pollutants

Aggressive mitigation of short-lived climate pollutants (SLCPs)—methane, tropospheric ozone, black carbon, and hydrofluorocarbons (HFCs)—is critical for near-term and long-term climate protection. These SLCPs also are known as “super climate pollutants.”

- Cutting SLCPs is the only plausible way to limit warming due to unmasking of cooling aerosols over the next 20 years:
  - “In fact, given that the net effect of the fossil-fuel phase-out on temperature is minimal during the first 20 years (Fig. 3), reducing those other [non-fossil] emissions is the only plausible way in which to decrease warming during that period.”<sup>64</sup>
- In contrast to the limited amount of warming reduced at 2050 by cutting CO<sub>2</sub>, fast cuts to [SLCPs could avoid up to 0.6 °C of warming by 2050, and up to 1.2 °C by 2100](#),<sup>65</sup> which would [reduce projected warming in the Arctic by two-thirds and the rate of global warming by half](#).<sup>66</sup>
  - The [IPCC’s Special Report on Global Warming of 1.5 °C](#) concludes that cutting SLCPs is essential for staying below 1.5 °C.<sup>67</sup>

- Similarly, the [warning of the climate emergency issued in November 2019 from 11,000 scientists](#) also emphasizes the importance of cutting SLCPs:
  - “We need to promptly reduce the emissions of short-lived climate pollutants, including methane (figure 2b), black carbon (soot), and hydrofluorocarbons (HFCs). Doing this could slow climate feedback loops and potentially reduce the short-term warming trend by more than 50% over the next few decades while saving millions of lives and increasing crop yields due to reduced air pollution (Shindell et al. 2017<sup>68</sup>). The 2016 Kigali amendment to phase down HFCs is welcomed.”<sup>69</sup>*
- HFCs are now being phased down under the Montreal Protocol’s Kigali Amendment, with the potential to [avoid up to 0.5 °C of warming by 2100](#).<sup>70</sup>
  - The initial phasedown schedule of the [Kigali Amendment avoids about 90% of the potential, or up to 0.44 °C](#).
  - More mitigation is available from a faster phasedown schedule, from collecting and destroying HFCs at end of product life, recycling and destroying HFC “banks” embedded in products and equipment, early replacement of older inefficient cooling equipment using HFC refrigerants, and reducing refrigerant leaks through better design, manufacturing, and servicing.<sup>71</sup>
  - The Kigali Amendment also requires Parties to destroy HFC-23, a by-product of the production of HCFC-22, to the extent practicable, and this will provide additional mitigation not included in the 0.5 °C calculation.<sup>72</sup>
  - Improving energy efficiency of cooling equipment during the HFC phasedown can more than double the climate benefits in CO<sub>2</sub>e by reducing emissions from the power plants that provide the electricity to run the equipment.<sup>73</sup>
- Black carbon and tropospheric ozone are local air pollutants and typically addressed under national or regional air pollution laws, as well as through the voluntary programs of the Climate and Clean Air Coalition to Reduce Short-Lived Climate Pollutants (CCAC).<sup>74</sup>
  - Cutting black carbon and tropospheric ozone can save up to 2.4 million lives every year, and increase annual crop production by more than 50 million tons, worth US \$4-33 billion a year, as calculated in 2011.<sup>75</sup>
  - California [has cut black carbon emissions by 90%](#) under its air pollution laws and provides a model for other jurisdictions.<sup>76</sup>
- The Arctic is nearly five times more sensitive to black carbon emitted in the Arctic region than from similar emissions in the mid-latitudes.<sup>77</sup> In the Arctic, black carbon not only warms the atmosphere but also facilitates additional warming by darkening the snow and ice and reducing albedo, or reflectivity, allowing the darker surface to absorb extra solar radiation and cause further melting.<sup>78</sup>
  - Heavy-Fuel Oil (HFO) used in shipping is a significant source of black carbon, and the International Maritime Organization (IMO) has drafted a proposal to ban it in the Arctic beginning in July 2024 for some ships, with waivers and exemptions for others until July 2029.<sup>79</sup> (HFO has been banned in the Antarctic since 2011.<sup>80</sup>)
  - If the HFO ban had been in effect in the Arctic in 2019, as currently drafted, it would have banned only 16% of HFO used in the Arctic, and reduced only 5% of the black carbon.<sup>81</sup>
  - However, if the Arctic ban were imposed without the waivers or exemptions, black carbon emissions could have been reduced by 30%.<sup>82</sup>
- Is it possible to reduce 70% of global black carbon emissions by 2030<sup>83</sup>, including by implementing the following measures:

- Reducing on-road and off-road diesel emissions by mandating diesel particulate filters while eliminating diesel and other high-emitting vehicles and shifting to clean forms of transportation.<sup>84</sup>
- Eliminating flaring, while shifting to clean energy.<sup>85</sup>
- Switching to clean cooking and heating methods.<sup>86</sup>
- Banning heavy fuel oil in the Arctic and establishing black carbon emission standards for vessels by amending Annex VI of the International Convention for the Prevention of Pollution from Ships (MARPOL).<sup>87</sup>
- Ensuring fast ratification of the Gothenburg Protocol and the 2012 amendment that includes controls for black carbon.<sup>88</sup>
- Methane is increasingly being addressed under local and national laws, as well as under voluntary programs. At a global level, reducing methane emissions associated with human activity by 50% over the next 30 years could mitigate global temperature change by 0.18 °C by 2050.<sup>89</sup> From 2040–2070, methane mitigation could avoid up to 0.27 °C of warming, according to a forthcoming methane assessment by the CCAC.
  - California’s target is to reduce methane emissions by 40% by 2030.<sup>90</sup>
  - The U.S. Climate Alliance aims to reduce methane emissions across all sectors by 40–50% by 2030,<sup>91</sup> which includes reducing emissions from the energy sector by 40–45% by 2025,<sup>92</sup> from the waste sector by 40–50% by 2030,<sup>93</sup> and from the agricultural sector where emissions can be reduced 30% from enteric fermentation<sup>94</sup> and up to 70% from manure management by 2030.<sup>95</sup>
  - In the North America Climate, Clean Energy, and Environment Partnership signed in 2016, the United States, Canada and Mexico agreed to reduce methane emissions from the oil and gas sector by 40–45% by 2025 and committed to develop and implement federal regulations to reduce emissions from existing new sources in the oil and gas sector as well as to develop and implement national methane reduction strategies for key sectors, including oil and gas, agriculture, and waste and food management as soon as possible.<sup>96</sup>
  - The current European Union climate target is to reduce all greenhouse gas emissions by 40% compared to 1990 levels by 2030, with a proposal to increase this target to 55%.<sup>97</sup> This will require 35–37% methane emission reductions by 2030 compared to 2005 levels.<sup>98</sup> The EU plans to review all relevant environmental and climate legislation bearing on methane emissions, including the Effort Sharing Regulation which sets out binding anthropogenic methane reductions for Member States,<sup>99</sup> and the National Emissions Reduction Commitments Directive.<sup>100</sup>
    - According to a report commissioned by the European Union on global trends in methane emissions, “[r]elative to the year 2010, the most stringent emission scenarios (i.e. MTR or a 2° scenario) lead to a CO<sub>2</sub>e emission reduction of 2.4 to 3.7 Gt annually in 2030 and 2.9 to 5.1 Gt in 2050...,” and this would close 15–33% of the emission gap identified in the 2017 UNEP Emissions Gap Report.<sup>101</sup>
  - The CCAC calculates for the oil and gas sector that “Absolute reduction target of at least 45% reduction in methane emissions by 2025 and 60% to 75% by 2030...are realistic and achievable targets ....”<sup>102</sup>
  - The Clean Air Task Force states that available technology can reduce oil and gas methane emissions by 75%; additionally, 50% of all sector methane emissions reduction are possible at no net cost.<sup>103</sup>
- Specific measures to reduce methane emissions include:

- Strengthening methane mitigation policies by implementing readily available technologies, laws, and governance structures to their fullest and considering ways to expand methane mitigation through other available avenues.<sup>104</sup>
- Addressing leaks<sup>105</sup> and reducing venting<sup>106</sup> in the oil and gas sector. The Clean Air Task Force states that prohibiting venting of natural gas can reduce emission by 95%.<sup>107</sup>
- Eliminating flaring from oil and gas operations, while shifting to clean energy.<sup>108</sup>
- Improving feeding and manure management on farms. In the United States, this could cut emissions from manure by as much as 70% and emissions from enteric fermentation by 30%.<sup>109</sup>
- Upgrading solid waste and wastewater treatment.<sup>110</sup>
- Reducing food waste, diverting organic waste from landfills, and improving landfill management, which could reduce landfill emissions in the United States by 50% by 2030.<sup>111</sup>
- While not an SLCP, long-lived nitrous oxide (N<sub>2</sub>O) is the most significant anthropogenic ozone depleting greenhouse gas not yet controlled by the Montreal Protocol.<sup>112</sup> Through mandatory control measures, the Montreal Protocol could spur adoption of technologies to reduce N<sub>2</sub>O emissions, which are contributing the equivalent of about 10% of today's CO<sub>2</sub> warming.<sup>113</sup>
  - Controlling nitrous oxide (N<sub>2</sub>O) emissions could provide climate mitigation of about 1.67 GtCO<sub>2</sub>e GWP<sub>100</sub> by 2050 with 0.94 GtCO<sub>2</sub>e from agriculture and about 0.6 GtCO<sub>2</sub>e from industry in 2050.<sup>114</sup> In the industrial sector, abatement technology has been available and utilized by manufacturers in developed countries since the 1990s.<sup>115</sup> Moreover, only five countries produce 86% of industrial N<sub>2</sub>O: China, the United States, Singapore, Egypt, and Russia.<sup>116</sup>
  - In the agriculture sector, several solutions have been found to be cost-effective in reducing N<sub>2</sub>O emissions from agricultural processes: precision farming using variable rate technology (VRT) and nitrogen inhibitors that suppress the microbial activity that produces N<sub>2</sub>O. Studies have found that use of VRT can increase yield by 1–10%, while saving approximately 4%-37% of nitrogen fertilization.<sup>117</sup> Another solution, the SOP (Save Our Planet)<sup>118</sup> product line, stimulates nitrogen-uptake in crops and inhibits GHG emissions from manure.<sup>119</sup>
  - Other strategies are being proposed for removing methane and other non-CO<sub>2</sub> greenhouse gases from the atmosphere.<sup>120</sup>

## 10. Importance of protecting forests and other sinks

Halting the destruction of our forests and other [carbon sinks](#) so they continue to store vast quantities of carbon and do not turn into sources of CO<sub>2</sub> provides critical fast mitigation, while also saving biodiversity.<sup>121</sup>

- Already, 17% of the Amazon forest has been destroyed, and there is an expected tipping point when 20 to 40% is lost.<sup>122</sup>
- With increased deforestation, including from fires, greater disturbances, and higher temperatures, there is a point at which the Amazon rainforest would be difficult to reestablish.<sup>123</sup>

Under current warming trends, the global land sink, which now mitigates ~30% of carbon emissions, could be cut by half as early as 2040, as increasing temperatures reduce photosynthesis and speed up respiration,<sup>124</sup> calling into question the national pledges under the Paris Accord, which rely heavily on land uptake of carbon to meet mitigation goals.<sup>125</sup>

Effective ways to protect forests, peatlands, and other sinks include:

- Promoting forest protection and proforestation to allow existing forests to achieve their full ecological potential.<sup>126</sup>
- Preserving existing peatlands and restoring degraded peatlands.<sup>127</sup>
- Restoring coastal ‘blue carbon’ ecosystems.<sup>128</sup>

## 11. Conclusion

The IPCC’s Special Report on 1.5 °C presents the three essential strategies for keeping the planet relatively safe: reducing CO<sub>2</sub>, reducing SLCPs, and removing up to 1,000 billion tons of CO<sub>2</sub> from the atmosphere by 2100.<sup>129</sup>

- Cutting SLCPs is the only known strategy that can slow warming and feedbacks in [time to avoid catastrophic and perhaps existential impacts](#)<sup>130</sup> from [Hothouse Earth](#),<sup>131</sup> other than perhaps solar radiation management, which could cause unknown and potentially unmanageable side effects.

## References

<sup>1</sup> Molina M., Zaelke D., Sarma K. M., Andersen S. O., Ramanathan V., & Kaniaru D. (2009) [Reducing abrupt climate change risk using the Montreal Protocol and other regulatory actions to complement cuts in CO<sub>2</sub> emissions](#), PROC. NAT'L. ACAD. SCI. 106(49):20616–20621, 20616 (“Current emissions of anthropogenic greenhouse gases (GHGs) have already committed the planet to an increase in average surface temperature by the end of the century that may be above the critical threshold for tipping elements of the climate system into abrupt change with potentially irreversible and unmanageable consequences. This would mean that the climate system is close to entering if not already within the zone of “dangerous anthropogenic interference” (DAI). Scientific and policy literature refers to the need for “early,” “urgent,” “rapid,” and “fast-action” mitigation to help avoid DAI and abrupt climate changes. We define “fast-action” to include regulatory measures that can begin within 2–3 years, be substantially implemented in 5–10 years, and produce a climate response within decades. We discuss strategies for short-lived non-CO<sub>2</sub> 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<sub>2</sub> emissions.”). See also Molina M., Ramanathan V. & Zaelke D. (2020) [Best path to net zero: Cut short-lived climate pollutants](#), BULLETIN OF THE ATOMIC SCIENTISTS (“And let us be clear: By “speed,” we mean measures—including regulatory ones—that can begin within two-to-three years, be substantially implemented in five-to-10 years, and produce a climate response within the next decade or two.”).

<sup>2</sup> Lenton T. M., Rockstrom J., Gaffney O., Rahmstorf S., Richardson K., Steffen W., & Schellnhuber H. J. (2019) [Climate tipping points—too risky to bet against](#), NATURE, Comment, 575(7784):592–595, 594 (“In our view, the clearest emergency would be if we were approaching a global cascade of tipping points that led to a new, less habitable, ‘hothouse’ climate state<sup>11</sup>. Interactions could happen through ocean and atmospheric circulation or through feedbacks that increase greenhouse-gas levels and global temperature. Alternatively, strong cloud feedbacks could cause a global tipping point<sup>12-13</sup>. We argue that cascading effects might be common. Research last year<sup>14</sup> analysed 30 types of regime shift spanning physical climate and ecological systems, from collapse of the West Antarctic ice sheet to a switch from rainforest to savanna. This indicated that exceeding tipping points in one system can increase the risk of crossing them in others. Such links were found for 45% of possible interactions<sup>14</sup>. In our view, examples are starting to be observed. ... If damaging tipping cascades can occur and a global tipping point cannot be ruled out, then this is an existential threat to civilization. No amount of economic cost–benefit analysis is going to help us. We need to change our approach to the climate problem. ... In our view, the evidence from tipping points alone suggests that we are in a state of planetary emergency: both the risk and urgency of the situation are acute....”). See also Steffen W., et al. (2018) [Trajectories of the Earth System in the Anthropocene](#), PROC. NAT'L. ACAD. SCI. 115(33):8252–8259, 8254 (“This analysis implies that, even if the Paris Accord target of a 1.5 °C to 2.0 °C rise in temperature is met, we cannot exclude the risk that a cascade of feedbacks could push the Earth System irreversibly onto a “Hothouse Earth” pathway. The challenge that humanity faces is to create a “Stabilized Earth” pathway that steers the Earth System away from its current trajectory toward the threshold beyond which is Hothouse Earth (Fig. 2). The humancreated Stabilized Earth pathway leads to a basin of attraction that is not likely to exist in the Earth System’s stability landscape without human stewardship to create and maintain it. Creating such a pathway and basin of attraction requires a fundamental change in the role of humans on the planet. This stewardship role requires deliberate and sustained action to become an integral, adaptive part of Earth System dynamics, creating feedbacks that keep the system on a Stabilized Earth pathway (Alternative Stabilized Earth Pathway).”).

<sup>3</sup> Xu Y. & Ramanathan V. (2017) [Well below 2 °C: Mitigation strategies for avoiding dangerous to catastrophic climate changes](#), PROC. NAT'L. ACAD. SCI. 114(39):10319–10323 (“Box 2. Risk Categorization of Climate Change to Society. ... [A] 2 °C warming would double the land area subject to deadly heat and expose 48% of the population. A 4 °C warming by 2100 would subject 47% of the land area and almost 74% of the world population to deadly heat, which could pose existential risks to humans and mammals alike unless massive adaptation measures are implemented, such as providing air conditioning to the entire population or a massive relocation of most of the population to safer climates. ... This bottom 3 billion population comprises mostly subsistent farmers, whose livelihood will be severely impacted, if not destroyed, with a one- to five-year megadrought, heat waves, or heavy floods; for those among the bottom 3 billion of the world’s population who are living in coastal areas, a 1- to 2-m rise in sea level (likely with a warming in excess of 3 °C) poses existential threat if they do not relocate or migrate. It has been estimated that several hundred million people would be subject to famine with warming in excess of 4 °C (54). However, there has essentially been no discussion on warming beyond 5 °C. Climate change-induced species extinction is one major concern with warming of such large magnitudes (>5 °C). The current rate of loss of species is ~1,000-fold the historical rate, due largely to habitat destruction. At this rate, about 25% of species are in danger of extinction in the coming decades (56). Global warming of 6 °C or more (accompanied by increase in ocean acidity due to



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increased CO<sub>2</sub>) can act as a major force multiplier and expose as much as 90% of species to the dangers of extinction (57). The bodily harms combined with climate change-forced species destruction, biodiversity loss, and threats to water and food security, as summarized recently (58), motivated us to categorize warming beyond 5 °C as unknown??., implying the possibility of existential threats.”). See also Xu C., Kohler T. A., Lenton T. M., Svenning J.-C., & Scheffer M. (2020) *Future of the human climate niche*, PROC. NAT’L. ACAD. SCI. 117(21):11350–11355 (“Here, we demonstrate that for millennia, human populations have resided in the same narrow part of the climatic envelope available on the globe, characterized by a major mode around ~11 °C to 15 °C mean annual temperature (MAT). ... We show that in a business-as-usual climate change scenario, the geographical position of this temperature niche is projected to shift more over the coming 50 y than it has moved since 6000 BP. ... Specifically, 3.5 billion people will be exposed to MAT ≥29.0 °C, a situation found in the present climate only in 0.8% of the global land surface, mostly concentrated in the Sahara, but in 2070 projected to cover 19% of the global land (Fig. 3). ... For instance, accounting for population growth projected in the SSP3 scenario, each degree of temperature rise above the current baseline roughly corresponds to one billion humans left outside the temperature niche, absent migration (SI Appendix, Fig. S14).”).

<sup>4</sup> Lenton T. M., Rockstrom J., Gaffney O., Rahmstorf S., Richardson K., Steffen W., & Schellnhuber H. J. (2019) *Climate tipping points—too risky to bet against*, NATURE, Comment, 575(7784):592–595, 592 (“Models suggest that the Greenland ice sheet could be doomed at 1.5 °C of warming<sup>3</sup>, which could happen as soon as 2030. ... The world’s remaining emissions budget for a 50:50 chance of staying within 1.5 °C of warming is only about 500 gigatonnes (Gt) of CO<sub>2</sub>. Permafrost emissions could take an estimated 20% (100 Gt CO<sub>2</sub>) off this budget, and that’s without including methane from deep permafrost or undersea hydrates. If forests are close to tipping points, Amazon dieback could release another 90 Gt CO<sub>2</sub> and boreal forests a further 110 Gt CO<sub>2</sub>. With global total CO<sub>2</sub> emissions still at more than 40 Gt per year, the remaining budget could be all but erased already. ... We argue that the intervention time left to prevent tipping could already have shrunk towards zero, whereas the reaction time to achieve net zero emissions is 30 years at best. Hence we might already have lost control of whether tipping happens. A saving grace is that the rate at which damage accumulates from tipping — and hence the risk posed — could still be under our control to some extent.”).

<sup>5</sup> Intergovernmental Panel on Climate Change (IPCC) *Summary for Policymakers*, in *GLOBAL WARMING OF 1.5 °C*, Masson-Delmotte, V. P., *et al.* (eds.), 4 (“Human activities are estimated to have caused approximately 1.0 °C of global warming above pre-industrial levels, with a *likely* range of 0.8 °C to 1.2 °C. Global warming is *likely* to reach 1.5 °C between 2030 and 2052 if it continues to increase at the current rate. (*high confidence*).”). In addition to cutting CO<sub>2</sub> emissions and emissions of the super climate pollutants, the IPCC 1.5 °C Report also calculates the need for significant CO<sub>2</sub> removal. *Id.* at 17 (“C.3. All pathways that limit global warming to 1.5°C with limited or no overshoot project the use of carbon dioxide removal (CDR) on the order of 100–1000 GtCO<sub>2</sub> over the 21st century.”).

<sup>6</sup> Xu Y., Ramanathan V., & Victor D. G. (2018) *Global warming will happen faster than we think*, NATURE, Comment, 564(7734):30–32, 30–31 (“But the latest IPCC special report underplays another alarming fact: global warming is accelerating. Three trends—rising emissions, declining air pollution and natural climate cycles—will combine over the next 20 years to make climate change faster and more furious than anticipated. In our view, there’s a good chance that we could breach the 1.5 °C level by 2030, not by 2040 as projected in the special report (see ‘Accelerated warming’). The climate-modelling community has not grappled enough with the rapid changes that policymakers care most about, preferring to focus on longer-term trends and equilibria.”).

<sup>7</sup> World Meteorological Organization (WMO) (2020) *UNITED IN SCIENCE 2020*, 16 (“Figure 2 shows that in the five-year period 2020–2024, the annual mean global near surface temperature is predicted to be between 0.91 °C and 1.59 °C above pre-industrial conditions (taken as the average over the period 1850 to 1900). The chance of at least one year exceeding 1.5 °C above pre-industrial levels is 24%, with a very small chance (3%) of the five-year mean exceeding this level. Confidence in forecasts of global mean temperature is high. However, the coronavirus lockdown caused changes in emissions of greenhouse gases and aerosols that were not included in the forecast models. The impact of changes in greenhouse gases is likely small based on early estimates (Le Quéré *et al.* 2020 and Carbonbrief.org).”).

<sup>8</sup> Intergovernmental Panel on Climate Change (IPCC) *Summary for Policymakers*, in *GLOBAL WARMING OF 1.5 °C*, Masson-Delmotte, V. P., *et al.* (eds.), 4 (“Human activities are estimated to have caused approximately 1.0 °C of global warming above pre-industrial levels, with a *likely* range of 0.8 °C to 1.2 °C. Global warming is *likely* to reach 1.5 °C between 2030 and 2052 if it continues to increase at the current rate. (*high confidence*).”). In addition to cutting CO<sub>2</sub> emissions and emissions of the super climate pollutants, the IPCC 1.5 °C Report also calculates the need for significant CO<sub>2</sub> removal. *Id.*, at 17 (“C.3. All pathways that limit global warming to 1.5°C with limited or no overshoot project the use of carbon dioxide removal (CDR) on the order of 100–1000 GtCO<sub>2</sub> over the 21st century.”).

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<sup>9</sup> Xu Y. & Ramanathan V. (2017) [\*Well below 2 °C: Mitigation strategies for avoiding dangerous to catastrophic climate changes\*](#), PROC. NAT'L. ACAD. SCI. 114(39):10315–10323, 10321 (“The SP [super pollutant] lever targets SLCPs. Reducing SLCP emissions thins the SP blanket within few decades, given the shorter lifetimes of SLCPs (weeks for BC to about 15 years for HFCs). The mitigation potential of the SP lever with a maximum deployment of current technologies ... is about 0.6 °C by 2050 and 1.2 °C by 2100 (SI Appendix, Fig. S5B and Table S1).”).

<sup>10</sup> Shindell D., et al. (2012) [\*Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security\*](#), SCIENCE 335(6065):183–189, 184–185 (“The global mean response to the CH<sub>4</sub> plus BC measures was  $-0.54 \pm 0.05^{\circ}\text{C}$  in the climate model. ...Roughly half the forcing is relatively evenly distributed (from the CH<sub>4</sub> measures). The other half is highly inhomogeneous, especially the strong BC forcing, which is greatest over bright desert and snow or ice surfaces. Those areas often exhibit the largest warming mitigation, making the regional temperature response to aerosols and ozone quite distinct from the more homogeneous response to well-mixed greenhouse gases.... BC albedo and direct forcings are large in the Himalayas, where there is an especially pronounced response in the Karakoram, and in the Arctic, where the measures reduce projected warming over the next three decades by approximately two thirds and where regional temperature response patterns correspond fairly closely to albedo forcing (for example, they are larger over the Canadian archipelago than the interior and larger over Russia than Scandinavia or the North Atlantic).”). See also United Nations Environment Programme (UNEP) & World Meteorological Organization (WMO) (2011) [\*Integrated Assessment of Black Carbon and Tropospheric Ozone\*](#), 262 (“Large impacts of the measures examined here were also seen for the Arctic despite the minimal amount of emissions currently taking place there. This occurs due to the high sensitivity of the Arctic both to pollutants that are transported there from remote sources and to radiative forcing that takes place in areas of the northern hemisphere outside the Arctic. The 16 measures examined here, including the measures on pellet stoves and coal briquettes, reduce warming in the Arctic by 0.7 °C (range 0.2 to 1.3 °C) at 2040. This is a large portion of the 1.1 °C (range 0.7 to 1.7 °C) warming projected under the reference scenario for the Arctic, and hence implementation of the measures would be virtually certain to substantially slow, but not halt, the pace of Arctic climate change.”).

<sup>11</sup> Drijfhout S., Bathiany S., Beaulieu C., Brovkin V., Claussen M., Huntingford C., Scheffer M., Sgubin G., & Swingedouw D. (2015) [\*Catalogue of abrupt shifts in Intergovernmental Panel on Climate Change climate models\*](#), PROC. NAT'L. ACAD. SCI. 112(43):E5777–E5786, E5777 (“Abrupt transitions of regional climate in response to the gradual rise in atmospheric greenhouse gas concentrations are notoriously difficult to foresee. However, such events could be particularly challenging in view of the capacity required for society and ecosystems to adapt to them. We present, to our knowledge, the first systematic screening of the massive climate model ensemble informing the recent Intergovernmental Panel on Climate Change report, and reveal evidence of 37 forced regional abrupt changes in the ocean, sea ice, snow cover, permafrost, and terrestrial biosphere that arise after a certain global temperature increase. Eighteen out of 37 events occur for global warming levels of less than 2°, a threshold sometimes presented as a safe limit.”). See also Lenton T. M., Rockstrom J., Gaffney O., Rahmstorf S., Richardson K., Steffen W., & Schellnhuber H. J. (2019) [\*Climate tipping points—too risky to bet against\*](#), NATURE, Comment, 575(7784):592–595, 593 (“A further key impetus to limit warming to 1.5 °C is that other tipping points could be triggered at low levels of global warming. The latest IPCC models projected a cluster of abrupt shifts between 1.5 °C and 2 °C, several of which involve sea ice. This ice is already shrinking rapidly in the Arctic....”).

<sup>12</sup> Molina M., Ramanathan V., & Zaelke D. (9 October 2018) [\*Climate report understates threat\*](#), BULLETIN OF THE ATOMIC SCIENTISTS (“The UN’s Intergovernmental Panel on Climate Change’s Special Report on Global Warming of 1.5 degrees Celsius, released on Monday, is a major advance over previous efforts to alert world leaders and citizens to the growing climate risk. But the report, dire as it is, misses a key point: Self-reinforcing feedbacks and tipping points—the wildcards of the climate system—could cause the climate to destabilize even further. The report also fails to discuss the five percent risk that even existing levels of climate pollution, if continued unchecked, could lead to runaway warming—the so-called “[\*fat tail\*](#)” risk. These omissions may mislead world leaders into thinking they have more time to address the climate crisis, when in fact immediate actions are needed. To put it bluntly, there is a significant risk of self-reinforcing climate feedback loops pushing the planet into chaos beyond human control.”). See also Lenton T. M., Rockstrom J., Gaffney O., Rahmstorf S., Richardson K., Steffen W., & Schellnhuber H. J. (2019) [\*Climate tipping points—too risky to bet against\*](#), NATURE, Comment, 575(7784):592–595, 592 (“In our view, the consideration of tipping points helps to define that we are in a climate emergency and strengthens this year’s chorus of calls for urgent climate action — from schoolchildren to scientists, cities and countries.”); and Witze A. (10 September 2020) [\*The Arctic is burning like never before — and that’s bad news for climate change\*](#), NATURE NEWS (“Wildfires blazed along the Arctic Circle this summer, incinerating tundra, blanketing Siberian cities in smoke and capping the second extraordinary fire season in a row. By the time the fire season waned at the end of last month, the blazes had emitted a record 244 megatonnes of carbon dioxide — that’s 35% more than last year, which also set records. One culprit, scientists say, could be peatlands that are burning as the top of the world melts.”).

<sup>13</sup> Vose R. S., Huang B., Yin X., Arndt D., Easterling D. R., Lawrimore J. H., Menne M. J., Sanchez-Lugo A., & Zhang H. M. (2021) [Implementing Full Spatial Coverage in NOAA's Global Temperature Analysis](#), GEOPHYS. RSCH. LETT. 48: e2020GL090873 (A revised NOAA dataset with greater spatial coverage confirms that the rate of Arctic warming is more than three times the global average, with “significantly more warming in the Arctic since 1980 (0.598 vs. 0.478°C dec<sup>-1</sup>)” compared to the global average surface temperature trend of 0.179°C dec<sup>-1</sup> ( $\pm 0.032$ ); and NASA Press Release (14 January 2021) [2020 Tied for Warmest Year on Record, NASA Analysis Shows](#) (“Earth’s warming trends are most pronounced in the Arctic, which the GISTEMP analysis shows is warming more than three times as fast as the rest of the globe over the past 30 years, according to Schmidt.”). See also Ballinger T. J., Overland J. E., Wang M., Bhatt U.S., Hanna E., Hanssen-Bauer I., Kim S.-J., Thoman R. L., & Walsh J. E. (2020) [Surface Air Temperature](#), in [ARCTIC REPORT CARD 2020](#), Thoman R. L., Richter-Menge J., & Druckenmiller M. L. (eds.), National Oceanic and Atmospheric Administration (NOAA) (Figure 1 shows Arctic mean surface air temperature (SAT) anomalies rising by about 3°C from 1900 to 2020 compared with global average SAT increase of about 1°C); and Pistone K., Eisenman I., & Ramanathan V. (2014) [Observational determination of albedo decrease caused by vanishing Arctic sea ice](#), PROC. NAT’L. ACAD. SCI. 111(9):3322–3326, 3322 (“The Arctic has warmed by nearly 2 °C since the 1970s, a temperature change three times larger than the global mean (1).”)

<sup>14</sup> Kumar A., Yadav J., & Mohan R. (2020) [Global warming leading to alarming recession of the Arctic sea-ice cover: Insights from remote sensing observations and model reanalysis](#), HELIYON 6(7):e04355–e04355 (“The land-ocean temperature of Global (90°S-90°N) and Arctic (70°N) regions are computed for the last 40 years (1979–2018). The average global air temperature has increased about  $0.02 \pm 0.02$  °C year<sup>-1</sup> (~0.78 °C in the last 40-year) while the Arctic air temperature has increased about  $0.08 \pm 0.02$  °C year<sup>-1</sup> (~3.1 °C in the last 40-year) (Figure 3a).”).

<sup>15</sup> Kumar A., Yadav J., & Mohan R. (2020) [Global warming leading to alarming recession of the Arctic sea-ice cover: Insights from remote sensing observations and model reanalysis](#), HELIYON 6(7):e04355–e04355 (“The data analysis shows rapid warming trend in the Arctic ocean region ( $0.089 \pm 0.01$  °C year<sup>-1</sup>; i.e., ~3.5 °C in the last 40-year) compared to the Arctic land region ( $0.072 \pm 0.01$  °C year<sup>-1</sup>; i.e., ~2.8 °C in the last 40-year).”).

<sup>16</sup> Pistone K., Eisenman I., & Ramanathan V. (2014) [Observational determination of albedo decrease caused by vanishing Arctic sea ice](#), PROC. NAT’L. ACAD. SCI. 111(9):3322–3326 (“The Arctic has warmed by nearly 2 °C since the 1970s, a temperature change three times larger than the global mean (1). During this period, the Arctic sea ice cover has retreated significantly, with the summer minimum sea ice extent decreasing by 40% (2).”) See also Jansen E. et al. (2020) [Past perspectives on the present era of abrupt Arctic climate change](#), NAT. CLIM. CHANGE 10:714–721, 714 (“Annual mean temperature trends over the Arctic during the past 40 years show that over this period, where satellite data are available, major portions have warmed by more than 1 °C per decade (Fig. 1a, red colours and outlined portion; a warming of 4 °C within 40 years is hereafter referred to as 1 °C per decade). ... Using a criterion based on the speed of near-surface air temperature warming over the past four decades, we find that the current Arctic is experiencing rates of warming comparable to abrupt changes, or D–O events, recorded in Greenland ice cores during the last glacial period. [During the last glacial period (120,000–11,000 years ago), more than 20 abrupt periods of warming, known as Dansgaard–Oeschger (D–O) events, took place 18–19.] Both past changes in the Greenland ice cores and the ongoing trends in the Arctic are directly linked to sea-ice retreat—in the Nordic Seas during glacial times and in the Eurasian Arctic at present. Abrupt changes have already been experienced and could, according to state-of-the-art climate models, occur in the Arctic during the twenty-first century, but climate models underestimate current rates of change in this region.”)

<sup>17</sup> Slater T., Lawrence I., Otosaka I. Shepherd A., Gourmelen N., Jacob L., Tepes P., Gilbert L., & Nienow P. (2021) [Earth's ice imbalance](#), THE CRYOSPHERE 15(1):233–246, 233 (“Arctic sea ice (7.6 trillion tonnes), Antarctic ice shelves (6.5 trillion tonnes), mountain glaciers (6.1 trillion tonnes), the Greenland ice sheet (3.8 trillion tonnes), the Antarctic ice sheet (2.5 trillion tonnes), and Southern Ocean sea ice (0.9 trillion tonnes) have all decreased in mass .... [T]here can be little doubt that the vast majority of Earth's ice loss is a direct consequence of climate warming.”)

<sup>18</sup> Slater T., Lawrence I., Otosaka I. Shepherd A., Gourmelen N., Jacob L., Tepes P., Gilbert L., & Nienow P. (2021) [Earth's ice imbalance](#), THE CRYOSPHERE 15(1):233–246, 233 (“The rate of [global] ice loss has risen by 57 % since the 1990s – from 0.8 to 1.2 trillion tonnes per year – owing to increased losses from mountain glaciers, Antarctica, Greenland and from Antarctic ice shelves.... Even though Earth's cryosphere has absorbed only a small fraction of the global energy imbalance [ $3.2 \pm 0.3$  % ], it has lost a staggering 28 trillion tonnes of ice between 1994 and 2017.... [T]here can be little doubt that the vast majority of Earth's ice loss is a direct consequence of climate warming.”)

<sup>19</sup> Landrum L. & Holland M. M. (2020) [Extremes become routine in an emerging new Arctic](#), NAT. CLIM. CHANGE, Online Publication, 1–8, 1 (“The Arctic is rapidly warming and experiencing tremendous changes in sea ice, ocean and terrestrial regions. Lack of long-term scientific observations makes it difficult to assess whether Arctic changes statistically represent a

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'new Arctic' climate. Here we use five Coupled Model Intercomparison Project 5 class Earth system model large ensembles to show how the Arctic is transitioning from a dominantly frozen state and to quantify the nature and timing of an emerging new Arctic climate in sea ice, air temperatures and precipitation phase (rain versus snow). Our results suggest that Arctic climate has already emerged in sea ice. Air temperatures will emerge under the representative concentration pathway 8.5 scenario in the early- to mid-twenty-first century, followed by precipitation-phase changes. Despite differences in mean state and forced response, these models show striking similarities in their anthropogenically forced emergence from internal variability in Arctic sea ice, surface temperatures and precipitation-phase changes.”).

<sup>20</sup> National Snow and Ice Data Center (NSIDC) (21 September 2020) [Arctic sea ice decline stalls out at second lowest minimum](#) (“On September 15, Arctic sea ice likely reached its annual minimum extent of 3.74 million square kilometers (1.44 million square miles). The minimum ice extent is the second lowest in the 42-year-old satellite record, reinforcing the long-term downward trend in Arctic ice extent. Sea ice extent will now begin its seasonal increase through autumn and winter. ...*Please note that this is a preliminary announcement. Changing winds or late-season melt could still reduce the Arctic ice extent, as happened in 2005 and 2010. NSIDC scientists will release a full analysis of the Arctic melt season, and discuss the Antarctic winter sea ice growth, in early October.* ... The 14 lowest extents in the satellite era have all occurred in the last 14 years.”). See also Richter-Menge J., Druckenmiller M. L. & Thoman R. L. (2020) [15 Years of Arctic Observation: A Retrospective](#), in [ARCTIC REPORT CARD 2020](#), National Oceanic and Atmospheric Administration (NOAA), 8 (“As it turns out, the first publication in 2006 coincided with a cusp of transformation in the sea ice cover, which is literally and figuratively central to the Arctic system. The 2007 September minimum sea ice extent stunned scientists and grabbed world-wide media attention with a new record minimum that was 23% below the previous record low set in 2005. Just five years later, in 2012, the 2007 record was overtaken by a September minimum sea ice extent that was 18% below 2007. The 2012 record low still stands as of 2020. However, in the 14 years since ARC2006 the late summer sea ice minimum extent has never returned to pre-2007 values.”).

<sup>21</sup> Zach Labe (@ZLabe), Twitter, [22 October 2020, 10:51PM](#), Graphic showing Laptev Sea Ice extent and record low regrowth for October 2020 (“A historic event is ongoing in the #Arctic. We have to pay attention to these climate change indicators.”), linked in Watts J. (22 October 2020) [Alarm as Arctic sea ice not yet freezing at latest date on record](#), THE GUARDIAN (“For the first time since records began, the main nursery of Arctic sea ice in Siberia has yet to start freezing in late October. The delayed annual freeze in the Laptev Sea has been caused by freakishly protracted warmth in northern Russia and the intrusion of Atlantic waters, say climate scientists who warn of possible knock-on effects across the polar region. Ocean temperatures in the area recently climbed to more than 5C above average, following a record breaking heatwave and the unusually early decline of last winter’s sea ice. The trapped heat takes a long time to dissipate into the atmosphere, even at this time of the year when the sun creeps above the horizon for little more than an hour or two each day. Graphs of sea-ice extent in the Laptev Sea, which usually show a healthy seasonal pulse, appear to have flat-lined. As a result, there is a record amount of open sea in the Arctic. ... The Laptev Sea is known as the birthplace of ice, which forms along the coast there in early winter, then drifts westward carrying nutrients across the Arctic, before breaking up in the spring in the Fram Strait between Greenland and Svalbard. If ice forms late in the Laptev, it will be thinner and thus more likely to melt before it reaches the Fram Strait. This could mean fewer nutrients for Arctic plankton, which will then have a reduced capacity to draw down carbon dioxide from the atmosphere.”).

<sup>22</sup> Overland J. E. & Wang M. (2013) [When will the summer Arctic be nearly sea ice free?](#), GEOPHYS. RSCH. LETT. 40(10):2097–2101, 2097 (“Three recent approaches to predictions in the scientific literature are as follows: (1) extrapolation of sea ice volume data, (2) assuming several more rapid loss events such as 2007 and 2012, and (3) climate model projections. Time horizons for a nearly sea ice-free summer for these three approaches are roughly 2020 or earlier, 2030 ± 10 years, and 2040 or later. Loss estimates from models are based on a subset of the most rapid ensemble members. ... Observations and citations support the conclusion that most global climate model results in the CMIP5 archive are too conservative in their sea ice projections. Recent data and expert opinion should be considered in addition to model results to advance the very likely timing for future sea ice loss to the first half of the 21st century, with a possibility of major loss within a decade or two.”). See also Guarino M.-V. et al. (2020) [Sea-ice-free Arctic during the Last Interglacial supports fast future loss](#), NAT. CLIM. CHANGE 10:928–932, 931 (“The predicted year of disappearance of September sea ice under high-emissions scenarios is 2086 for HadCM3 (CMIP3/5), 2048 for HadGEM2-ES (CMIP5) and 2035 for HadGEM3 (CMIP6) (Fig. 4). More broadly, multimodel CMIP3–6 mean predictions (and ranges) for a summer sea-ice-free Arctic are as follows: CMIP3, 2062 (2040–2086); CMIP5, 2048 (2020–2081); and CMIP6, 2046 (2029–2066) (Fig. 4 and Supplementary Table 3). We note that the latest year of sea-ice disappearance for CMIP6 models is 2066 and that 50% of the models predict sea-ice-free conditions between ~2030 and 2040. From this we can see that HadGEM3 is not a particular outlier, in terms of its ECS or projected ice-free year.”); and Overland J. E., Wang M., Walsh J. E., & Stroeve J. C. (2014) [Future Arctic climate changes: Adaptation and mitigation time scales](#), EARTH’S FUTURE 2(2):68–74, 68 (“The climate in the Arctic is changing faster than in

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midlatitudes. This is shown by increased temperatures, loss of summer sea ice, earlier snow melt, impacts on ecosystems, and increased economic access. Arctic sea ice volume has decreased by 75% since the 1980s.”).

<sup>23</sup> Guarino M.-V. *et al.* (2020) [Sea-ice-free Arctic during the Last Interglacial supports fast future loss](#), NAT. CLIM. CHANGE 10:928–932, 932 (“Our study has demonstrated that the high-ECS HadGEM3 model yields a much-improved representation of Arctic summers during the warmer LIG climate compared with previous old-generation model simulations. We analysed simulated surface air temperatures and proxy reconstructions of LIG summer temperatures and showed a 95% agreement between the model and observations. Arctic surface temperatures and sea ice are strongly related. By simulating an ice-free summer Arctic, our LIG CMIP6 simulation provides (direct) modelling and (indirect) observational support that the summer Arctic could have been ice free during the LIG. This offers a unique solution to the long-standing puzzle of what occurred to drive the temperatures to rise during LIG Arctic summers. The ability of the HadGEM3 model to realistically simulate the very warm LIG Arctic climate provides independent support for predictions of ice-free conditions by summer 2035. This should be of huge concern to Arctic communities and climate scientists.”).

<sup>24</sup> Årthun M., Onarheim I. H., Dörr J., & Eldevik T. (2021) [The seasonal and regional transition to an ice-free Arctic](#), GEOPHYS. RSCH. LETT. 48:1–10, 1 (“The Arctic sea ice cover is currently retreating and will continue its retreat in a warming world. However, the loss of sea ice is neither regionally nor seasonally uniform. Here we present the first regional and seasonal assessment of future Arctic sea ice loss in CMIP6 models under low (SSP126) and high (SSP585) emission scenarios, thus spanning the range of future change. We find that Arctic sea ice loss – at present predominantly limited to the summer season – will under SSP585 take place in all regions and all months. The summer sea ice is lost in all the shelf seas regardless of emission scenario, whereas ice-free conditions in winter before the end of this century only occur in the Barents Sea. The seasonal transition to ice-free conditions is found to spread through the Atlantic and Pacific regions, with change starting in the Barents Sea and Chukchi Sea, respectively.”). *See also* Tor Eldevik (@TorEldevik), Twitter, [7 December 2020, 6:43AM](#) (Co-author on the study sharing graphics and information about the ice-free conditions in the shelf seas).

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

<sup>26</sup> Pistone K., Eisenman I., & Ramanathan V. (2019) [Radiative Heating of an Ice-Free Arctic Ocean](#), GEOPHYS. RSCH. LETT. 46(13):7474–7480, 7479 (“The estimate of one trillion tons of CO<sub>2</sub> emissions is computed using the following approximate formula:  $f = (5.35 \text{ W/m}^2) \ln[x/R]$  (Myhre *et al.*, 1998). Here  $f$  is the radiative forcing relative to an arbitrary reference value  $R$ ,  $x$  is the atmospheric CO<sub>2</sub> concentration, and  $\ln$  indicates the natural logarithm. Note that this formula is an expression of the relationship that a doubling of atmospheric CO<sub>2</sub> causes a radiative forcing of 3.71 W/m<sup>2</sup>. Considering a radiative forcing of 0.71 W/m<sup>2</sup>, this translates to an increase in the atmospheric CO<sub>2</sub> concentration from 400 to 456.7 ppm. Since 1 ppm of atmospheric CO<sub>2</sub> is equivalent to 7.77 Gt (Le Quéré *et al.*, 2018), this increase of 56.7 ppm weighs 441 Gt. The mean airborne fraction of CO<sub>2</sub> (i.e., fraction of CO<sub>2</sub> emissions that remain in the atmosphere) is estimated to be  $0.44 \pm 0.06$  (section 6.3.2.4 of Ciais *et al.*, 2013). This implies that the emissions needed to increase atmospheric CO<sub>2</sub> enough to cause 0.71 W/m<sup>2</sup> of radiative forcing is 1.0 trillion tons (i.e., 441 Gt/0.44).”).

<sup>27</sup> Annual CO<sub>2</sub> concentrations peak in May. *See* National Oceanic and Atmospheric Administration (NOAA) (4 June 2020) [Rise of CO<sub>2</sub> unabated](#), NOAA RESEARCH NEWS (“Atmospheric carbon dioxide measured at Mauna Loa Observatory reached a seasonal peak of 417.1 parts per million for 2020 in May, the highest monthly reading ever recorded, scientists from NOAA and Scripps Institution of Oceanography at the University of California San Diego announced today. This year’s peak value was 2.4 parts per million (ppm) higher than the 2019 peak of 414.7 ppm recorded in May 2019. NOAA scientists reported a May average of 417.1 ppm. Scripps scientists reported an May average of 417.2 ppm. Monthly carbon dioxide (CO<sub>2</sub>) values at Mauna Loa first breached the 400 ppm threshold in 2014, and are now at levels not experienced by the atmosphere in several million years.”).

<sup>28</sup> Pistone K., Eisenman I., & Ramanathan V. (2019) [Radiative Heating of an Ice-Free Arctic Ocean](#), GEOPHYS. RSCH. LETT. 46(13):7474–7480, 7476 (“Hence, we focus on the baseline estimate scenario in which cloud conditions remain unchanged from the present. We find that the complete disappearance of Arctic sea ice throughout the sunlit part of the year in this scenario would cause the average planetary albedo of the Arctic Ocean (poleward of 60 °N) to decrease by 11.5% in absolute

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terms. This would add an additional 21 W/m<sup>2</sup> of annual-mean solar heating over the Arctic Ocean relative to the 1979 baseline state. Averaged over the globe, this implies a global radiative heating of 0.71 W/m<sup>2</sup> (Figure 2).”).

<sup>29</sup> Etminan M., Myhre G., Highwood E. J., & Shrine K. P. (2016) [Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing](#), *GEOPHYS. RSCH. LETT.* 43(24):12614–12623, 12620 (“The new expressions increase the IPCC AR5 [Myhre et al., 2013a, Table 8.2] RFs for CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O for the period 1750–2011 from 1.82, 0.48, and 0.17 Wm<sup>-2</sup> to 1.83, 0.61, and 0.17 Wm<sup>-2</sup> or by 0.5%, 25%, and 2%, respectively; the difference in the sum of the three forcings is 0.14Wm<sup>-2</sup>.”). National Oceanic and Atmospheric Administration (NOAA) calculated that the radiative forcing from CO<sub>2</sub> was 2.044 W/m<sup>2</sup> in 2018 and 2.076 W/m<sup>2</sup> in 2019. See NOAA Earth System Research Laboratory, [The NOAA Annual Greenhouse Gas Index \(AGGI\)](#) (last updated Spring 2020). See also Wunderling N., Willeit M., Donges J. F., & Winklemann R. (2020) [Global warming due to loss of large ice masses and Arctic summer sea ice](#), *NAT. COMMUN.* 11(5177):1–8, 6 (“On shorter time scales, the decay of the Arctic summer sea ice would exert an additional warming of 0.19 °C (0.16–0.21 °C) at a uniform background warming of 1.5 °C (=400 ppm) above pre-industrial. On longer time scales, which can typically not be considered in CMIP projections, the loss of Greenland and West Antarctica, mountain glaciers and the Arctic summer sea ice together can cause additional GMT warming of 0.43°C (0.39–0.46 °C). This effect is robust for a whole range of CO<sub>2</sub> emission scenarios up to 700 pm and corresponds to 29% extra warming relative to a 1.5 °C scenario.”). If the Greenland Ice Sheet, West Antarctic Ice Sheet, and mountain glaciers were also completely ice-free, the planet could see an additional 0.43 °C of warming, with 55% of that coming from the loss of albedo.

<sup>30</sup> Pistone K., Eisenman I., & Ramanathan V. (2019) [Radiative Heating of an Ice-Free Arctic Ocean](#), *GEOPHYS. RSCH. LETT.* 46(13):7474–7480, 7477 (“We examine two perhaps unrealistically extreme future Arctic cloud scenarios: at one extreme, an ice-free Arctic Ocean that is completely cloud free and at the other extreme, an ice-free Arctic Ocean that is completely overcast. For simplicity, in the latter scenario we use distributions of cloud optical thickness based on present-day observations (see Appendix A). Both of these extreme scenarios are shown in Figure 2. The cloud-free, ice-free Arctic scenario results in a global radiative heating of 2.2 W/m<sup>2</sup> compared with the 1979 baseline state, which is 3 times more than the 0.71 W/m<sup>2</sup> baseline estimate derived above for unchanged clouds. The completely overcast ice-free Arctic scenario results in a global radiative heating of 0.37 W/m<sup>2</sup>, which is approximately half as large as the 0.71 W/m<sup>2</sup> baseline estimate (Figure 2b). This suggests that even in the presence of an extreme negative cloud feedback, the global heating due to the complete disappearance of the Arctic sea ice would still be nearly double the already-observed heating due to the current level of ice loss.”).

<sup>31</sup> Perovich D. *et al.* (2020) [Sea Ice](#), in [ARCTIC REPORT CARD 2020](#), Thoman R. L., Richter-Menge J., & Druckenmiller M. L. (eds.), National Oceanic and Atmospheric Administration (NOAA), 48 (“The oldest ice (> 4 years old) was once a major component of the Arctic sea ice cover, but now makes up just a small fraction of the March Arctic Ocean ice pack (Fig. 3). In 1985, 33% of the ice pack was very old ice (> 4 years), but by March 2020 old ice only constituted 4.4% of the ice pack within the Arctic Ocean. The total extent of the oldest ice declined from 2.70 million km<sup>2</sup> in March 1985 to 0.34 million km<sup>2</sup> in March 2020. The March 2020 extent of > 4 year old ice increased from the record-low year in 2019 when it was only 1.2% (0.09 million km<sup>2</sup>) of the ice cover. This increase was due to 3–4 year old ice surviving a year and aging into > 4 year old ice. The 3–4 year old cover dropped from 6.4% in 2019 to 3.7% in 2020. Overall the percentage of ice 3 years and older was effectively unchanged. Note that these percentages are relative to ice in the Arctic Ocean region (Fig. 3, bottom inset); areas in the peripheral seas outside of this region have little or no older ice and thus do not show any change over time.”). See also Perovich D. *et al.* (2019) [Sea Ice](#), in [ARCTIC REPORT CARD 2019](#), Richter-Menge J., Druckenmiller M. L., & Jeffries M. (eds.), National Oceanic and Atmospheric Administration (NOAA), 29–30 (“The oldest ice (>4 years old), which once dominated within the Arctic Ocean, now makes up just a small fraction of the Arctic Ocean ice pack in March, when the sea ice cover is at its maximum extent (Fig. 3). In 1985, 33% of the ice pack was very old ice (>4 years), but by March 2019 old ice only constituted 1.2% of the ice pack within the Arctic Ocean. The total extent of the oldest ice declined from 2.52 million km<sup>2</sup> in March 1985 to 0.09 million km<sup>2</sup> in March 2019. ... First-year ice now dominates the sea ice cover, comprising ~70% of the March 2019 ice pack, compared to approximately 35–50% in the 1980s. Given that older ice tends to be thicker, the sea ice cover has transformed from a strong, thick ice mass in the 1980s to a younger, more fragile, and thinner ice mass in recent years. First-year ice is therefore more vulnerable to melting out in summer, thereby increasing the likelihood of lower minimum ice extents.”); and World Meteorological Organization (WMO) (2020) [UNITED IN SCIENCE 2020](#), 9 (“Arctic (as well as sub-Arctic) sea ice has seen a long-term decline in all months during the satellite era (1979–present), with the largest relative losses in late summer, around the time of the annual minimum in September, with regional variations. The long-term trend over the 1979–2019 period indicates that Arctic summer sea-ice extent has declined at a rate of approximately 13% per decade (Figure 4). In every year from 2016 to 2020, the Arctic average summer minimum and average winter maximum sea-ice extent were below the 1981–2010 long term average. In July 2020, the Arctic sea-ice extent was the lowest on record for July. There is very high confidence that Arctic sea-ice extent continues to decline in all months of the year and that since 1979, the areal proportion of thick ice, at least 5 years old, has declined by approximately 90%.”); and National Snow & Ice

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Data Center (NSIDC) (2 September 2020) [Tapping the brakes](#), Arctic Sea Ice News & Analysis (“As of September 1, Arctic sea ice extent stood at 4.26 million square kilometers (1.64 million square miles), the second lowest extent for that date in the satellite passive microwave record that started in 1979.”). Analysis by Zack Labe showed that sea ice for the high Arctic (above 80 °N) was the lowest extent on record. Twitter, Zack Labe, [@ZLabe \(11 September 2020, 6:19pm\)](#) (“Sea ice extent in the middle of the #Arctic Ocean is currently the lowest on record (e.g., high Arctic ~80°N+ latitude). This is a pretty impressive statistic.”).

<sup>32</sup> Thomson J. & Rogers W. E. (2014) [Swell and sea in the emerging Arctic Ocean](#), GEOPHYS. RSCH. LETT. 41(9):3136–3140, 3136 (“Ocean surface waves (sea and swell) are generated by winds blowing over a distance (fetch) for a duration of time. In the Arctic Ocean, fetch varies seasonally from essentially zero in winter to hundreds of kilometers in recent summers. Using in situ observations of waves in the central Beaufort Sea, combined with a numerical wave model and satellite sea ice observations, we show that wave energy scales with fetch throughout the seasonal ice cycle. Furthermore, we show that the increased open water of 2012 allowed waves to develop beyond pure wind seas and evolve into swells. The swells remain tied to the available fetch, however, because fetch is a proxy for the basin size in which the wave evolution occurs. Thus, both sea and swell depend on the open water fetch in the Arctic, because the swell is regionally driven. This suggests that further reductions in seasonal ice cover in the future will result in larger waves, which in turn provide a mechanism to break up sea ice and accelerate ice retreat.”).

<sup>33</sup> Day J. J. & Hodges K. I. (2018) [Growing Land-Sea Temperature Contrast and the Intensification of Arctic Cyclones](#), GEOPHYS. RSCH. LETT. 45:3673–3681, 3680 (“In this study we have investigated near-surface air temperature gradients along the Arctic coastline in a number of reanalysis products and observations and constructed an index for coastal baroclinicity (the AFZ index). We have used this to construct an analog for future climate change using the highest and lowest quartile years of this index as an analog for climate change and performed composite analysis of atmospheric fields, to infer the response of Arctic cyclones to climate change. In summary, we observed: 1. that 2m land temperatures near the Arctic coastline are warming at approximately twice the rate of sea surface temperatures in adjacent regions; 2. that significantly increased Arctic cyclone frequency and intensity, particularly in the Eastern part of the Arctic Ocean, are characteristic of years with high Arctic coastal temperature gradients, compared to low years; and 3. that the sign of this response is consistent with climate model projections, but the magnitude of change in cyclone numbers is higher, suggesting that CMIP models underestimate the sensitivity of the summer storm track to increasing land-sea contrast in the Arctic. Further, because climate change is increasing land-sea contrasts in the Arctic, it seems highly likely that the circulation patterns typical of years with strong AFZ will become more common as the climate warms. Indeed, strengthening of the mean temperature gradients in the AFZ is a robust feature of future climate projections as is an increase in the strength of the Arctic Front Jet (Mann et al., 2017; Nishii et al., 2014). This study shows that this linkage between surface temperature gradients and atmospheric circulation is important for Arctic cyclones, adding weight to previous studies.”).

<sup>34</sup> Zhang J., Lindsay R., Schweiger A., & Steele M. (2013) [The impact of an intense summer cyclone on 2012 Arctic sea ice retreat](#), GEOPHYS. RSCH. LETT. 40(4):720–726, 722 (“The rapid reduction in ice volume during the storm is due to enhanced ice melt (Figures 3a–3d). The simulated total ice melt is  $0.12 \times 10^3 \text{ km}^3 \text{ d}^{-1}$  before the cyclone, but almost doubled during the cyclone, averaging  $0.21 \times 10^3 \text{ km}^3 \text{ d}^{-1}$  (or  $0.17 \times 10^3 \text{ km}^3 \text{ d}^{-1}$  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  $0.12 \text{ m d}^{-1}$  (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.”).

<sup>35</sup> Wang Q., Wekerle C., Wang X., Danilov S., Koldunov N., Sein D., Sidorenko D., von Appen W.-J., & Jung T. (2020) [Intensification of the Atlantic Water Supply to the Arctic Ocean Through Fram Strait Induced by Arctic Sea Ice Decline](#), GEOPHYS. RSCH. LETT. 47(3):e2019GL086682, 1–10, 1 (“Substantial changes have occurred in the Arctic Ocean in the last decades. Not only sea ice has retreated significantly, but also the ocean at middepth showed a warming tendency. By using simulations we identified a mechanism that intensifies the upward trend in ocean heat supply to the Arctic Ocean through Fram Strait. The reduction in sea ice export through Fram Strait induced by Arctic sea ice decline increases the salinity in the Greenland Sea, which lowers the sea surface height and strengthens the cyclonic gyre circulation in the Nordic Seas. The Atlantic Water volume transport to the Nordic Seas and Arctic Ocean is consequently strengthened. This enhances the warming trend of the Arctic Atlantic Water layer, potentially contributing to the Arctic “Atlantification. . . . In these processes, the Nordic Seas play the role of a switchyard, while the reduction of sea ice export flux caused by increased air-sea heat flux over the Arctic Ocean is the switchgear. Increasing ocean heat can reduce sea ice thickness, and currently this occurs mainly in certain regions including the western Eurasian Basin near the Fram Strait and the northern Kara Sea (Carmack et al., 2015; Dmitrenko et al., 2014; Ivanov et al., 2012; Onarheim et al., 2014; Polyakov et al., 2010).”). See also Ciavarella A., et al.

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(2020) [Prolonged Siberian heat of 2020](#), World Weather Attribution, 21–22 (“A large, rapid multi-method attribution study, supported by observational and large ensemble model analyses, indicates with high confidence that extremely warm periods such as the 6 months of January–June 2020 over the Siberian region would have been at least 2 °C cooler in a world without human influence. Similar events have a best estimate return time in the current climate of around 130 years and are now more than 600 times as likely to occur as they would have been at the beginning of the 20<sup>th</sup> century; with the best estimate orders of magnitude larger. By 2050 we expect such a regional warm period in the first 6 months of the year to be at least another 0.5 °C warmer, and possibly up to 5 °C warmer, with similar 6-month regional temperatures becoming correspondingly more frequent. Statements regarding the very high June daily maximum temperatures (38 °C) such as were reported at Verkhoyansk can be made only with much lower confidence. Nevertheless, results also indicate a large increase in the likelihood of such temperatures and, with more confidence, an increase in extreme daily maxima of more than 1 °C when comparing the climate of 1900 to the present day.”).

<sup>36</sup> Lawrence D. M., Slater A. G., Tomas R. A., Holland M. M., & Deser C. (2008) [Accelerated Arctic land warming and permafrost degradation during rapid sea ice loss](#), GEOPHYS. RSCH. LETT. 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.”). See also Vaks A., Mason A., Breitenbach S., Kononov A., Osinzev A., Rosensaft M., Borshevsky A., Gutareva O., & Henderson G. (2020) [Palaeoclimate evidence of vulnerable permafrost during times of low sea ice](#), NATURE 577(7789):221–225, 221 (“The robustness of permafrost when sea ice is present, as well as the increased permafrost vulnerability when sea ice is absent, can be explained by changes in both heat and moisture transport. Reduced sea ice may contribute to warming of Arctic air, which can lead to warming far inland. Open Arctic waters also increase the source of moisture and increase autumn snowfall over Siberia, insulating the ground from low winter temperatures. These processes explain the relationship between an ice-free Arctic and permafrost thawing before 0.4 Ma. If these processes continue during modern climate change, future loss of summer Arctic sea ice will accelerate the thawing of Siberian permafrost.”); and Witze A. (10 September 2020) [The Arctic is burning like never before — and that’s bad news for climate change](#), NATURE NEWS (“Wildfires blazed along the Arctic Circle this summer, incinerating tundra, blanketing Siberian cities in smoke and capping the second extraordinary fire season in a row. By the time the fire season waned at the end of last month, the blazes had emitted a record 244 megatonnes of carbon dioxide — that’s 35% more than last year, which also set records. One culprit, scientists say, could be peatlands that are burning as the top of the world melts.”). For more on impacts of melting permafrost to climate and water supply see: Jorge Daniel Taillant: a) Meltdown: The Earth Without Glaciers (Chapter 5, A Thawing Earth). Oxford University Press. forthcoming, Sept 2021 and Jorge Daniel Taillant Glaciers: The Politics of Ice. (Chapter 4, Invisible Glaciers). Oxford University Press. 2015.

<sup>37</sup> Schaefer K., Lantuit H., Romanovsky V. E., Schuur E. A. G., & Witt R. (2014) [The Impact of the Permafrost Carbon Feedback on Global Climate](#), ENV’T RSCH. LETT. 9:1–9, 2 (“If temperatures rise and permafrost thaws, the organic material will also thaw and begin to decay, releasing carbon dioxide (CO<sub>2</sub>) and methane (CH<sub>4</sub>) 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<sub>2</sub> into organic matter and freeze it back into the permafrost.”). See also Schaefer K., Zhang T., Bruhwiler L., & Barrett A. P. (2011) [Amount and timing of permafrost carbon release in response to climate warming](#), TELLUS B 63(2):165–180, 166 (“The permafrost carbon feedback (PCF) is an amplification of surface warming due to the release into the atmosphere of carbon currently frozen in permafrost (Fig. 1). As atmospheric CO<sub>2</sub> 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<sub>2</sub> 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).”).

<sup>38</sup> Wilkerson J., Dobosky R., Sayres D. S., Healy C., Dumas E., Baker B., & Anderson J. G. (2019) [Permafrost nitrous oxide emissions observed on a landscape scale using the airborne eddy-covariance method](#), ATMOS. CHEM. PHYS. 19(7):4257–4268, 4257 (“The microbial by-product nitrous oxide (N<sub>2</sub>O), a potent greenhouse gas and ozone depleting substance, has conventionally been assumed to have minimal emissions in permafrost regions. This assumption has been questioned by recent in situ studies which have demonstrated that some geologic features in permafrost may, in fact, have elevated emissions comparable to those of tropical soils. However, these recent studies, along with every known in situ study focused on permafrost N<sub>2</sub>O fluxes, have used chambers to examine small areas (< 50 m<sup>2</sup>). In late August 2013, we used the airborne eddy-covariance technique to make in situ N<sub>2</sub>O flux measurements over the North Slope of Alaska from a low-flying aircraft spanning a much larger area: around 310 km<sup>2</sup>. We observed large variability of N<sub>2</sub>O fluxes with many areas exhibiting



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negligible emissions. Still, the daily mean averaged over our flight campaign was 3.8 (2.2–4.7) mg N<sub>2</sub>O m<sup>-2</sup> d<sup>-1</sup> with the 90 % confidence interval shown in parentheses. If these measurements are representative of the whole month, then the permafrost areas we observed emitted a total of around 0.04–0.09 g m<sup>-2</sup> for August, which is comparable to what is typically assumed to be the upper limit of yearly emissions for these regions.”).

<sup>39</sup> Chadburn S. E., *et al.* (2017) [An observation-based constraint on permafrost loss as a function of global warming](#), NAT. CLIM. CHANGE 7:340–344, 340 (“The estimated permafrost area is 15.5 million km<sup>2</sup> using this technique (12.0–18.2 million km<sup>2</sup> using minimum/maximum curves), which compares well to 15.0 million km<sup>2</sup> from observations (12.6–18.4 million km<sup>2</sup>).”).

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

<sup>41</sup> Turetsky M. R., *et al.* (2020) [Carbon release through abrupt permafrost thaw](#), NAT. GEOSCI. 13:138–143, 138–139 (“The permafrost zone is expected to be a substantial carbon source to the atmosphere, yet large-scale models currently only simulate gradual changes in seasonally thawed soil. Abrupt thaw will probably occur in <20% of the permafrost zone but could affect half of permafrost carbon through collapsing ground, rapid erosion and landslides. Here, we synthesize the best available information and develop inventory models to simulate abrupt thaw impacts on permafrost carbon balance. Emissions across 2.5 million km<sup>2</sup> of abrupt thaw could provide a similar climate feedback as gradual thaw emissions from the entire 18 million km<sup>2</sup> permafrost region under the warming projection of Representative Concentration Pathway 8.5. While models forecast that gradual thaw may lead to net ecosystem carbon uptake under projections of Representative Concentration Pathway 4.5, abrupt thaw emissions are likely to offset this potential carbon sink. Active hillslope erosional features will occupy 3% of abrupt thaw terrain by 2300 but emit one-third of abrupt thaw carbon losses. Thaw lakes and wetlands are methane hot spots but their carbon release is partially offset by slowly regrowing vegetation. After considering abrupt thaw stabilization, lake drainage and soil carbon uptake by vegetation regrowth, we conclude that models considering only gradual permafrost thaw are substantially underestimating carbon emissions from thawing permafrost.”).

<sup>42</sup> Schuur E. A. G., *et al.* (2015) [Climate Change and the Permafrost Carbon Feedback](#), NATURE 520:171–179, 171 (“The first studies that brought widespread attention to permafrost carbon estimated that almost 1,700 billion tons of organic carbon were stored in terrestrial soils in the northern permafrost zone. The recognition of this vast pool stored in Arctic and sub-Arctic regions was in part due to substantial carbon stored at depth (.1 m) in permafrost, below the traditional zone of soil carbon accounting.”). *See also* World Bank & International Cryosphere Climate Initiative (ICCI) (2013) [On Thin Ice: How Cutting Pollution Can Slow Warming and Save Lives](#), 44.

<sup>43</sup> U.S. Environmental Protection Agency (EPA) (2015) [U.S. National Black Carbon and Methane Emissions: A Report to the Arctic Council](#), 2, 9 (Figure 1 shows BC emissions north of the 40<sup>th</sup> parallel in 2011 amounting to 0.51 million metric tons, with 39% from open biomass burning, and 51% of that number [19.89% or ~0.10 MMT] due to wildfires; “In 2011, 51 percent of black carbon emissions from open biomass burning were from wildfires, 43 percent from prescribed burning, with the remainder from agricultural field burning.”). *See also* Kim J.-S., Kug J.-S., Jeong S.-J., Park H., & Schaeppman-Strub G. (2020) [Extensive fires in southeastern Siberian permafrost linked to preceding Arctic Oscillation](#), SCI. ADV. 6(2): eaax3308, 2, 4 (“Strictly speaking, the fire activity–related high-pressure pattern extends further into southeastern Siberia than the typical AO pattern. This suggests that the AO provides preferable conditions for strong fire activity (i.e., high-temperature anomalies), but the positive pressure anomaly extending westward from the North Pacific to southeastern Siberia explains more southeastern Siberian fire activity variability.”; “In contrast, we found a significant negative relationship between March to April snow cover and total annual fire activity, as positive temperature anomalies related to a positive AO in February and March drive early snowmelt in March and April with a time lag of 1 to 2 months (Fig. 3, B and C, and fig. S6) (18, 19). This is consistent with results from a snow water equivalent dataset (fig. S7). Accumulated positive temperature anomalies in late winter lead to earlier melting in snow cover’s seasonal evolution. Once snow cover is reduced, a positive snow-albedo feedback accelerates surface warming and snowmelt (fig. S8). Thus, significant negative snowmelt is observed in March and April as a result (Fig. 3, B and C). Earlier snowmelt leads to faster exposure of the ground surface and litter, which, in turn, allows favorable conditions for fire spreading because this region consists mostly of larch (*Larix gmelinii*) forests with a high amount of litter that can act as fire fuel (22)... This analysis shows a generally negative relation between burned area and P/PET, meaning that more arid regions have stronger fire activity.”); and EPA (2012) [Report to Congress on Black Carbon](#), EPA-450/R-12-001.

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<sup>44</sup> Schuur E., et al. (2008) [Vulnerability of Permafrost Carbon to Climate Change: Implications for the Global Carbon Cycle](#), *BIOSCIENCE* 58(8):701–714, 710 (“Model scenarios of fire in Siberia show that extreme fire years can result in approximately 40% greater C emissions because of increased soil organic C consumption (Soja et al. 2004). In combination with dry conditions or increased water infiltration, thawing and fires could, given the right set of circumstances, act together to expose and transfer permafrost C to the atmosphere very rapidly”). See also McCarty J. L., Smith T. E. L., & Turetsky M. R. (2020) [Arctic fires re-emerging](#), *NAT. GEOSCI.* 13(10):658–660, 659 (“Evidence from 2019 and 2020 suggests that extreme temperatures accompanied by drying are increasing the availability of surface fuels in the Arctic. New tundra vegetation types, including dwarf shrubs, sedges, grasses and mosses, as well as surface peats, are becoming vulnerable to burning, and what we typically consider to be ‘fire-resistant’ ecosystems, such as tundra bogs, fens and marshes, are burning (Fig. 1). While wildfires on permafrost in boreal regions of Siberia are not uncommon<sup>7</sup>, 2020’s fires are unusual in that more than 50% of the detected fires above 65° N occurred on permafrost with high ice content. Ice-rich permafrost is considered to contain the most carbon-rich soils in the Arctic<sup>8</sup> and burning can accelerate thaw and carbon emission rates<sup>9</sup>”).

<sup>45</sup> Peter Wadhams (2017) *A FAREWELL TO ICE: A REPORT FROM THE ARCTIC*, Oxford University Press: Oxford, UK, 125–126. See also Shakohva N., Semiletov I., & Chuvilin E. (2019) [Understanding the Permafrost-Hydrate System and Associated Methane Releases in the East Siberian Arctic Shelf](#), *GEOSCI.* 9(251):1–23.

<sup>46</sup> Whiteman G., Hope C., & Wadhams P. (2013) [Vast costs of Arctic change](#), *NATURE* 499(7459):401–403 (“We calculate that the costs of a melting Arctic will be huge, because the region is pivotal to the functioning of Earth systems such as oceans and the climate. The release of methane from thawing permafrost beneath the East Siberian Sea, off northern Russia, alone comes with an average global price tag of \$60 trillion in the absence of mitigating action — a figure comparable to the size of the world economy in 2012 (about \$70 trillion). The total cost of Arctic change will be much higher... The methane pulse will bring forward by 15–35 years the average date at which the global mean temperature rise exceeds 2°C above pre-industrial levels — to 2035 for the business-as-usual scenario and to 2040 for the low-emissions case (see ‘Arctic methane’). This will lead to an extra \$60 trillion (net present value) of mean climate-change impacts for the scenario with no mitigation, or 15% of the mean total predicted cost of climate-change impacts (about \$400 trillion). In the low-emissions case, the mean net present value of global climate-change impacts is \$82 trillion without the methane release; with the pulse, an extra \$37 trillion, or 45% is added.... These costs remain the same irrespective of whether the methane emission is delayed by up to 20 years, kicking in at 2035 rather than 2015, or stretched out over two or three decades, rather than one. A pulse of 25 Gt of methane has half the impact of a 50 Gt pulse. The economic consequences will be distributed around the globe, but the modelling shows that about 80% of them will occur in the poorer economies of Africa, Asia and South America. ... The full impacts of a warming Arctic, including, for example, ocean acidification and altered ocean and atmospheric circulation, will be much greater than our cost estimate for methane release alone. To find out the actual cost, better models are needed to incorporate feedbacks that are not included ....”).

<sup>47</sup> Dyonisius M. N. et al. (2020) [Old carbon reservoirs were not important in the deglacial methane budget](#), *SCIENCE* 367:907–910, 908-909 (“Resulting CH<sub>4</sub> emissions from old permafrost carbon range from 0 to 53 Tg CH<sub>4</sub> per year (table S10) (20) throughout the last deglaciation and may have contributed up to 27% of the total CH<sub>4</sub> emissions to the atmosphere (95% CI upper limit) at the end of the OD-B transition (14.42 ka BP). However, we consider this calculation speculative (see section 4.3 of the materials and methods) (20)... The last deglaciation serves only as a partial analog to current anthropogenic warming, with the most important differences being the much colder baseline temperature, lower sea level, and the presence of large ice sheets covering a large part of what are currently permafrost regions in the NH.... Because the relatively large global warming of the last deglaciation (which included periods of large and rapid regional warming in the high latitudes) did not trigger CH<sub>4</sub> emissions from old carbon reservoirs, such CH<sub>4</sub> emissions in response to anthropogenic warming also appear to be unlikely.”).

<sup>48</sup> Drijfhout S., Bathiany S., Beaulieu C., Brovkin V., Claussen M., Huntingford C., Scheffer M., Sgubin G., & Swingedouw D. (2015) [Catalogue of abrupt shifts in Intergovernmental Panel on Climate Change climate models](#), *PROC. NAT’L. ACAD. SCI.* 112(43):E5777–E5786, E5777 (“Abrupt transitions of regional climate in response to the gradual rise in atmospheric greenhouse gas concentrations are notoriously difficult to foresee. However, such events could be particularly challenging in view of the capacity required for society and ecosystems to adapt to them. We present, to our knowledge, the first systematic screening of the massive climate model ensemble informing the recent Intergovernmental Panel on Climate Change report, and reveal evidence of 37 forced regional abrupt changes in the ocean, sea ice, snow cover, permafrost, and terrestrial biosphere that arise after a certain global temperature increase. Eighteen out of 37 events occur for global warming levels of less than 2°, a threshold sometimes presented as a safe limit.”). See also Lenton T. M., Rockstrom J., Gaffney O., Rahmstorf S., Richardson K., Steffen W., & Schellnhuber H. J. (2019) [Climate tipping points—too risky to bet against](#), *NATURE*, Comment, 575(7784):592–595, 593 (“A further key impetus to limit warming to 1.5 °C is that other tipping points could be

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triggered at low levels of global warming. The latest IPCC models projected a cluster of abrupt shifts between 1.5 °C and 2 °C, several of which involve sea ice. This ice is already shrinking rapidly in the Arctic....”).

<sup>49</sup> Hoegh-Guldberg O., *et al.* (2018) [Impacts of 1.5 °C of Global Warming on Natural and Human Systems](#), in Intergovernmental Panel on Climate Change (IPCC) [GLOBAL WARMING OF 1.5 °C](#), Masson-Delmotte, V. P., *et al.* (eds.), 262 (“Tipping points refer to critical thresholds in a system that, when exceeded, can lead to a significant change in the state of the system, often with an understanding that the change is irreversible. An understanding of the sensitivities of tipping points in the physical climate system, as well as in ecosystems and human systems, is essential for understanding the risks associated with different degrees of global warming. This subsection reviews tipping points across these three areas within the context of the different sensitivities to 1.5°C versus 2°C of global warming. Sensitivities to less ambitious global temperature goals are also briefly reviewed. Moreover, an analysis is provided of how integrated risks across physical, natural and human systems may accumulate to lead to the exceedance of thresholds for particular systems. The emphasis in this section is on the identification of regional tipping points and their sensitivity to 1.5°C and 2°C of global warming, whereas tipping points in the global climate system, referred to as large-scale singular events, were already discussed in Section 3.5.2. A summary of regional tipping points is provided in Table 3.7.”).

<sup>50</sup> Abram N., *et al.* (2019) [Framing and Context of the Report](#), in [IPCC SPECIAL REPORT ON THE OCEAN AND CRYOSPHERE IN A CHANGING CLIMATE](#), Pörtner H.-O., *et al.* (eds.), 81 (“While some aspects of the ocean and cryosphere might respond in a linear (i.e., directly proportional) manner to a perturbation by some external forcing, this may change fundamentally when critical thresholds are reached. A very important example for such a threshold is the transition from frozen water to liquid water at around 0 °C that can lead to rapid acceleration of ice-melt or permafrost thaw (e.g., Abram *et al.*, 2013; Trusel *et al.*, 2018). Such thresholds often act as tipping points, as they are associated with rapid and abrupt changes even when the underlying forcing changes gradually (Figure 1.1a, 1.1c). Tipping elements include, for example, the collapse of the ocean’s large-scale overturning circulation in the Atlantic (Section 6.7), or the collapse of the West Antarctic Ice Sheet through a process called marine ice sheet instability (Cross-Chapter Box 8 in Chapter 3; Lenton, *et al.* 2008). Potential ocean and cryosphere tipping elements form part of the scientific case for efforts to limit climate warming to well below 2°C (IPCC, 2018).”). *See also* Collins M., *et al.* (2019) [Extreme, Abrupt Changes and Managing Risk](#), in [IPCC SPECIAL REPORT ON THE OCEAN AND CRYOSPHERE IN A CHANGING CLIMATE](#), Pörtner H.-O., *et al.* (eds.), 595–596 (Table 6.1).

<sup>51</sup> Robinson A., Calov R., & Ganopolski A. (2012) [Multistability and critical thresholds of the Greenland ice sheet](#), NAT. CLIM. CHANGE 2(6):429–432, 429 (“Recent studies have focused on the short-term contribution of the Greenland ice sheet to sea-level rise, yet little is known about its long-term stability. The present best estimate of the threshold in global temperature rise leading to complete melting of the ice sheet is 3.1 °C (1.9–5.1 °C, 95% confidence interval) above the preindustrial climate, determined as the temperature for which the modelled surface mass balance of the present-day ice sheet turns negative. Here, using a fully coupled model, we show that this criterion systematically overestimates the temperature threshold and that the Greenland ice sheet is more sensitive to long-term climate change than previously thought. We estimate that the warming threshold leading to a monostable, essentially ice-free state is in the range of 0.8–3.2 °C, with a best estimate of 1.6 °C. By testing the ice sheet’s ability to regrow after partial mass loss, we find that at least one intermediate equilibrium state is possible, though for sufficiently high initial temperature anomalies, total loss of the ice sheet becomes irreversible. Crossing the threshold alone does not imply rapid melting (for temperatures near the threshold, complete melting takes tens of millennia). However, the timescale of melt depends strongly on the magnitude and duration of the temperature overshoot above this critical threshold.”). *See also* Overland J. *et al.* (2019) [The urgency of Arctic change](#), POLAR SCI. 21:6–13, 9 (“The summer air temperature “viability threshold” that triggers irreversible wastage of the Greenland ice sheet was previously estimated to be for an annual global temperature increase of 2–5 °C (Gregory and Huybrechts, 2006; Huybrechts *et al.*, 2011). An updated estimate based on a higher resolution simulation that explicitly incorporates albedo and elevation feedbacks suggests a lower loss threshold: 0.8–3.2°C (95% confidence range) (Robinson *et al.*, 2012) with 1.6 °C above pre-industrial conditions as a best estimate. It is likely that the Greenland ice sheet enters a phase of irreversible loss under the RCP 4.5 scenario.”); and Schleussner C.-F. *et al.* (2016) [Differential Climate Impacts for Policy-Relevant Limits to Global Warming: the Case of 1.5°C and 2°C](#), EARTH SYST. DYNAM. 7(2):327–351, 342 (“In addition to that, Levermann *et al.* (2013) report a steep increase in long-term SLR between 1.5 °C and 2 °C as a result of an increasing risk of crossing a destabilizing threshold for the Greenland ice-sheet (Robinson *et al.*, 2012). The disintegration process that would lead to 5–7m global SLR, however, is projected to happen on the timescale of several millennia.”); and Kopp R. E., Shwon R. L., Wagner G., & Yuan J. (2016) [Tipping elements and climate–economic shocks: Pathways toward integrated assessment](#), EARTH’S FUTURE 4(8):346–372, 354–355 (“For the Greenland Ice Sheet, for example, feedbacks between ice sheet topography and atmospheric dynamics and between ice area and albedo give rise to multiple stable states [Ridley *et al.*, 2009; Robinson *et al.*, 2012; Levermann *et al.*, 2013]. Robinson *et al.* [2012]’s coupled ice-sheet/regional climate model indicated that, at a temperature of 1°C above pre-Industrial temperatures, the stable states are at 100%, 60%, and 20% of present ice volume. At 1.6°C, however, their model produced only one stable configuration, at ~15% of the Greenland ice sheet’s present volume; thus, 1.6°C warming would

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represent a commitment to ~6 m of sea-level rise from the Greenland Ice Sheet. The rate of ice sheet mass loss is, however, limited by the flux at the ice sheet margins [e.g., *Pfeffer et al.*, 2008], leading to a disconnect between committed and realized change that could persist for millennia, particularly for levels of warming near the threshold [*Applegate et al.*, 2015].”). If warming is limited to 2 °C, Greenland could contribute 5 cm of sea-level rise by 2050 and 13 cm by 2100, but if emissions are unabated and warming rises to 5 °C, Greenland could contribute 6 cm of sea-level rise by 2050 and 23 cm by 2100. See Bamber J. L., Oppenheimer M., Kopp R. E., Aspinall W. P., & Cooke R. M. (2019) [Ice sheet contributions to future sea-level rise from structured expert judgment](#), PROC. NAT'L. ACAD. SCI. 116(23):11195–11200, 11197 (Table 1).

<sup>52</sup> Trusel L. D., Das S. B., Osman M. B., Evans M. J., Smith B. E., Fettweis X., McConnell J. R., Noël B. P. Y., & van den Broeke M. R. (2018) [Nonlinear rise in Greenland runoff in response to post-industrial Arctic warming](#), NATURE 564:104–108, 104 (“Our results show a pronounced 250% to 575% increase in melt intensity over the last 20 years, relative to a pre-industrial baseline period (eighteenth century) for cores NU and CWG, respectively (Fig. 2). Furthermore, the most recent decade contained in the cores (2004–2013) experienced a more sustained and greater magnitude of melt than any other 10-year period in the ice-core records. For GrIS cores, 2012 melt is unambiguously the strongest melt season on record. Both NU and CWG annual ice-core-derived melt records significantly ( $P < 0.01$ ) correlate with one another over their 339 years of overlap, and both also with summer air temperatures from the Ilulissat region (Extended Data Table 2; Methods), relationships that improve after applying a 5-year moving average, probably reflecting the noise inherent to melt records owing to variability in meltwater percolation and refreezing. These empirically derived results revealing coherence between independent melt and temperature records emphasize broad-scale GrIS melt forcing, and suggest that summer warming (see Fig. 2) is an important component of the observed regional melt intensification.”).

<sup>53</sup> King M. D., Howat I. M., Candela S. G., Noh M. J., Jeong S., Noël B. P. Y., van den Broeke M. R., Wouters B., & Negrete A. (2020) [Dynamic ice loss from the Greenland Ice Sheet driven by sustained glacier retreat](#), COMM. EARTH & ENV'T. 1(1):1–7, 1 (“The Greenland Ice Sheet is losing mass at accelerated rates in the 21st century, making it the largest single contributor to rising sea levels. Faster flow of outlet glaciers has substantially contributed to this loss, with the cause of speedup, and potential for future change, uncertain. Here we combine more than three decades of remotely sensed observational products of outlet glacier velocity, elevation, and front position changes over the full ice sheet. We compare decadal variability in discharge and calving front position and find that increased glacier discharge was due almost entirely to the retreat of glacier fronts, rather than inland ice sheet processes, with a remarkably consistent speedup of 4–5% per km of retreat across the ice sheet. We show that widespread retreat between 2000 and 2005 resulted in a step-increase in discharge and a switch to a new dynamic state of sustained mass loss that would persist even under a decline in surface melt.”). When compared to the projections of the IPCC Fifth Assessment Report, the associated sea-level rise from the recent ice sheet melting of both Greenland and Antarctica is most like the upper range projections. See Slater T., Hogg A. E., & Mottram R. (2020) [Ice-sheet losses track high-end sea-level rise projections](#), NAT. CLIM. CHANGE, Comment, 10:879–881, 1 (“In AR5, the ice-sheet contribution by 2100 is forecast from process-based models simulating changes in ice flow and surface mass balance (SMB) in response to climate warming. Driven by the century-scale increase in temperature forced by representative concentration pathways (RCPs), global mean SLR estimates range from 280–980 mm by 2100 (Fig. 1). Of this, the ice-sheet contribution constitutes 4–420 mm (ref. 3). The spread of these scenarios is uncertain, scenario-dependent and increases rapidly after 2030 (Fig. 1). During 2007–2017, satellite observations show total ice-sheet losses increased the global sea level by  $12.3 \pm 2.3$  mm and track closest to the AR5 upper range (13.7–14.1 mm for all emissions pathways) (Fig. 1). Despite a reduction in ice-sheet losses during 2013–2017 — when atmospheric circulation above Greenland promoted cooler summer conditions and heavy winter snowfall — the observed average SLR rate ( $1.23 \pm 0.24$  mm per year) is 45% above central predictions ( $0.85 \pm 0.07$  mm per year) and closest to the upper range ( $1.39 \pm 0.14$  mm per year) (Fig. 2).”). In mid-September 2020, consistent warming over northeast Greenland contributed to a large chunk of a glacier breaking away from the Arctic’s largest remaining ice shelf. See Amos J. (14 September 2020) [Climate change: Warmth shatters section of Greenland ice shelf](#), BBC NEWS (“A big chunk of ice has broken away from the Arctic’s largest remaining ice shelf - 79N, or Nioghalvfjærdssjøfjorden - in north-east Greenland. The ejected section covers about 110 square km; satellite imagery shows it to have shattered into many small pieces. The loss is further evidence say scientists of the rapid climate changes taking place in Greenland. ... At its leading edge, the 79N glacier splits in two, with a minor offshoot turning directly north. It’s this offshoot, or tributary, called Spalte Glacier, that has now disintegrated. The ice feature was already heavily fractured in 2019; this summer’s warmth has been its final undoing. Spalte Glacier has become a flotilla of icebergs.”).

<sup>54</sup> Lenton T. M., Rockstrom J., Gaffney O., Rahmstorf S., Richardson K., Steffen W., & Schellnhuber H. J. (2019) [Climate tipping points—too risky to bet against](#), NATURE, Comment, 575(7784):592–595, 594 (“In our view, the clearest emergency would be if we were approaching a global cascade of tipping points that led to a new, less habitable, ‘hothouse’ climate state<sup>11</sup>. Interactions could happen through ocean and atmospheric circulation or through feedbacks that increase greenhouse-gas levels and global temperature. Alternatively, strong cloud feedbacks could cause a global tipping point<sup>12–13</sup>. We argue that cascading effects might be common. Research last year<sup>14</sup> analysed 30 types of regime shift spanning physical climate

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and ecological systems, from collapse of the West Antarctic ice sheet to a switch from rainforest to savanna. This indicated that exceeding tipping points in one system can increase the risk of crossing them in others. Such links were found for 45% of possible interactions<sup>14</sup>. In our view, examples are starting to be observed. ... If damaging tipping cascades can occur and a global tipping point cannot be ruled out, then this is an existential threat to civilization. No amount of economic cost–benefit analysis is going to help us. We need to change our approach to the climate problem. ... In our view, the evidence from tipping points alone suggests that we are in a state of planetary emergency: both the risk and urgency of the situation are acute....”).

<sup>55</sup> Cheng L., Abraham J., Hausfather Z., & Trenberth K. E. (2019) [\*How fast are the oceans warming?\*](#), SCIENCE 363(6423):128–129, 128 (“About 93% of the energy imbalance accumulates in the ocean as increased ocean heat content (OHC).”).

<sup>56</sup> Solomon S., Daniel J. S., Sanford T. J., Murphy D. M., Plattner G.-K., Knutti R., & Friedlingstein P. (2010) [\*Persistence of climate changes due to a range of greenhouse gases\*](#), PROC. NAT’L. ACAD. SCI. 107(43):18354–18359, 18357 (“In the case of a gas with a 10-y lifetime, for example, energy is slowly stored in the ocean during the period when concentrations are elevated, and this energy is returned to the atmosphere from the ocean after emissions cease and radiative forcing decays, keeping atmospheric temperatures somewhat elevated for several decades. Elevated temperatures last longer for a gas with a 100-y lifetime because, in this case, radiative forcing and accompanying further ocean heat uptake continue long after emissions cease. As radiative forcing decays further, the energy is ultimately restored from the ocean to the atmosphere. Fig. 3 shows that the slow timescale of ocean heat uptake has two important effects. It limits the transfer of energy to the ocean if emissions and radiative forcing occur only for a few decades or a century. However, it also implies that any energy that is added to the ocean remains available to be transferred back to the atmosphere for centuries after cessation of emissions.”).

<sup>57</sup> 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<sub>2</sub> emission and thus would be effective in minimizing future increases in the committed warming. However, because it also reduces air pollution and thus the ABC [Atmospheric Brown Cloud] masking effect, it may speed up the approach to the committed warming of 2.4°C (1.4–4.3°C).”). See also Samset B. H., Sand M., Smith C. J., Bauer S. E., Forster P. M., Fuglestedt J. S., Osprey S., & Schleussner C.-F. (2018) [\*Climate impacts from a removal of anthropogenic aerosol emissions\*](#), GEOPHYS. RSCH. LETT. 45(2):1020–1029, 1020 (“Limiting global warming to 1.5 or 2.0°C requires strong mitigation of anthropogenic greenhouse gas (GHG) emissions. Concurrently, emissions of anthropogenic aerosols will decline, due to coemission with GHG, and measures to improve air quality. ... Removing aerosols induces a global mean surface heating of 0.5–1.1°C, and precipitation increase of 2.0–4.6%. Extreme weather indices also increase. We find a higher sensitivity of extreme events to aerosol reductions, per degree of surface warming, in particular over the major aerosol emission regions. ... “Plain Language Summary. To keep within 1.5 or 2° of global warming, we need massive reductions of greenhouse gas emissions. At the same time, aerosol emissions will be strongly reduced. We show how cleaning up aerosols, predominantly sulfate, may add an additional half a degree of global warming, with impacts that strengthen those from greenhouse gas warming. The northern hemisphere is found to be more sensitive to aerosol removal than greenhouse gas warming, because of where the aerosols are emitted today. This means that it does not only matter whether or not we reach international climate targets. It also matters how we get there.”); and Feijoo F., Mignone B. K., Kheshgi H. S., Hartin C., McJeon H., & Edmonds J. (2019) [\*Climate and carbon budget implications of linked future changes in CO<sub>2</sub> and non-CO<sub>2</sub> forcing\*](#), ENVIRON. RCH. LETT. 14(4):04407, 1–11.

<sup>58</sup> Lelieveld J., Klingmüller K., Pozzer A., Burnett R. T., Haines A., & Ramanathan V. (2019) [\*Effects of fossil fuel and total anthropogenic emission removal on public health and climate\*](#), PROC. NAT’L. ACAD. SCI. 116(15):7192–7197, 7194 (“Finally, our model simulations show that fossil-fuel-related aerosols have masked about 0.51(±0.03) °C of the global warming from increasing greenhouse gases (Fig. 3). The largest temperature impacts are found over North America and Northeast Asia, being up to 2 °C. By removing all anthropogenic emissions, a mean global temperature increase of 0.73(±0.03) °C could even warm some regions up to 3 °C. Since the temperature increase from past CO<sub>2</sub> emissions is irreversible on human timescales, the aerosol warming will be unleashed during the phaseout (11, 19–22).”). See also Samset B. H., Sand M., Smith C. J., Bauer S. E., Forster P. M., Fuglestedt J. S., Osprey S., & Schleussner C.-F. (2018) [\*Climate impacts from a removal of anthropogenic aerosol emissions\*](#), GEOPHYS. RSH. LETT. 45(2):1020–1029, 1020 (“Limiting global warming to 1.5 or 2.0°C requires strong mitigation of anthropogenic greenhouse gas (GHG) emissions. Concurrently, emissions of anthropogenic aerosols will decline, due to coemission with GHG, and measures to improve air quality. ... Removing aerosols induces a global mean surface heating of 0.5–1.1°C, and precipitation increase of 2.0–4.6%. Extreme weather indices also increase. We find a higher sensitivity of extreme events to aerosol reductions, per degree of surface warming, in particular over the major aerosol emission regions. ... “Plain Language Summary. To keep within 1.5 or 2° of global warming, we need massive reductions of greenhouse gas emissions. At the same time, aerosol emissions will be strongly reduced. We show how cleaning

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up aerosols, predominantly sulfate, may add an additional half a degree of global warming, with impacts that strengthen those from greenhouse gas warming. The northern hemisphere is found to be more sensitive to aerosol removal than greenhouse gas warming, because of where the aerosols are emitted today. This means that it does not only matter whether or not we reach international climate targets. It also matters how we get there.”); and Feijoo F., Mignone B. K., Kheshgi H. S., Hartin C., McJeon H., & Edmonds J. (2019) *Climate and carbon budget implications of linked future changes in CO<sub>2</sub> and non-CO<sub>2</sub> forcing*, ENV’T RSCH. LETT. 14(4):04407, 1–11.

<sup>59</sup> Xu Y. & Ramanathan V. (2017) *Well below 2 °C: Mitigation strategies for avoiding dangerous to catastrophic climate changes*, PROC. NAT’L. ACAD. SCI. 114(39):10315–10323, Supplemental Information, 7 (Table S1. The contribution of individual mitigation measures to the warming in the 21<sup>st</sup> century.).

<sup>60</sup> Xu Y. (2020, personal communication). The baseline-fast warming scenario against which these mitigation scenarios are compared includes “unmasking” as emissions of cooling aerosols are reduced in the baseline-fast (RCP6.0) scenarios. If these aerosol emissions continued at current emission levels, undesired from air quality perspective, the warming in 2100 would be 0.6°C smaller. See also Xu Y. & Ramanathan V. (2017) *Well below 2 °C: Mitigation strategies for avoiding dangerous to catastrophic climate changes*, PROC. NAT’L. ACAD. SCI. 114(39):10315–10323, 10320 (“Hence, the CO<sub>2</sub> measures implemented in 2020 will unmask some of the aerosol cooling (red lines in SI Appendix, Fig. S5) and offset the warming reduction by CO<sub>2</sub> and SLCP mitigation. In the baseline scenarios of this study, the cooling aerosols are regulated gradually between 2020 and 2100 (SI Appendix, Fig. S6), whereas in the mitigation scenario examined here, CO<sub>2</sub> mitigation is implemented starting from 2020 and CO<sub>2</sub> emission is brought to net zero in about three decades (SI Appendix, Fig. S2B). As a result, the unmasking of coemitted aerosol cooling (a net warming effect) is more rapid in the decreasing CO<sub>2</sub> emissions beginning in 2020 (CN2020) mitigation scenario (SI Appendix, Fig. S5B vs. S7).”); and *Id.* at Table S1 [graph depicting warming potential based on cumulative emissions from CO<sub>2</sub> only, aerosols only, and short-lived climate pollutants only from the 1970’s into the 2090’s].

<sup>61</sup> Xu Y. & Ramanathan V. (2017) *Well below 2 °C: Mitigation strategies for avoiding dangerous to catastrophic climate changes*, PROC. NAT’L. ACAD. SCI. 114(39):10315–10323, Supplemental Information, 1 (“In the Baseline-default scenario for CO<sub>2</sub>, the emission keeps increasing throughout the 21<sup>st</sup> century (RCP8.5). The 5% to 95% range of baseline-default is also adopted (Fig. S1b). In the baseline-fast scenario for CO<sub>2</sub> (pre-INDCs), emissions effectively increase at a rate of 1.1%/year before 2030 and then following Representative Concentration Pathway 6.0 (Fig. S1a). In the mitigation scenario for CO<sub>2</sub> (i.e. INDCs and post-2030 decarbonization), emissions effectively increase at a rate of 0.8%/year before 2030 (following INDCs) and then decrease at a rate of 5.5%/year after 2030 (CN2030 in Fig. S2a).”).

<sup>62</sup> Xu Y. & Ramanathan V. (2017) *Well below 2 °C: Mitigation strategies for avoiding dangerous to catastrophic climate changes*, PROC. NAT’L. ACAD. SCI. 114(39):10315–10323, Supplemental Information, 1 (“In the Baseline-default scenario for CO<sub>2</sub>, the emission keeps increasing throughout the 21<sup>st</sup> century (RCP8.5). The 5% to 95% range of baseline-default is also adopted (Fig. S1b). In the baseline-fast scenario for CO<sub>2</sub> (pre-INDCs), emissions effectively increase at a rate of 1.1%/year before 2030 and then following Representative Concentration Pathway 6.0 (Fig. S1a). In the mitigation scenario for CO<sub>2</sub> (i.e. INDCs and post-2030 decarbonization), emissions effectively increase at a rate of 0.8%/year before 2030 (following INDCs) and then decrease at a rate of 5.5%/year after 2030 (CN2030 in Fig. S2a). The CN2020 scenario is the same as CN2030, except that the peak of emission is reached at 2020 (Fig. S2b).”). See also *Id.* Supplemental Information, 7 (Table S1. The contribution of individual mitigation measures to the warming in the 21<sup>st</sup> century.).

<sup>63</sup> Shindell D. & Smith C. J. (2019) *Climate and air-quality benefits of a realistic phase-out of fossil fuels*, NATURE 573:408–411, 409–410 (“These results differ greatly from the idealized picture of a near-instantaneous response to the removal of aerosol cooling followed by a slow transition to dominance by the effects of CO<sub>2</sub>. In these more plausible cases, the temperature effects of the reduction in CO<sub>2</sub>, SO<sub>2</sub> and CH<sub>4</sub> roughly balance one another until about 2035. After this, the cooling effects of reduced CO<sub>2</sub> continue to increase, whereas the warming induced by a reduction in SO<sub>2</sub> and the cooling induced by the reduction in CH<sub>4</sub> taper off, such that the cooling induced by the reduction in CO<sub>2</sub> dominates (Fig. 3). Examining the effects of CO<sub>2</sub> and SO<sub>2</sub> alone (Fig. 3d), the faster response of SO<sub>2</sub> to the changes in emissions means that the net effect of these two pollutants would indeed be a short-term warming—but a very small one, of between 0.02 °C and 0.10 °C in the ensemble mean temperature response (up to 0.30 °C for the 95th percentile across pathways). Accounting for all fossil-related emissions (Fig. 3e), any brief climate penalty decreases to no more than 0.05 °C (0.19 °C at the 95th percentile), with the smaller value largely due to the additional near-term cooling from reductions in methane. Nearly all the warming in the 2020s and 2030s (Fig. 2) is therefore attributable to the effect of the residual emissions (mainly of CO<sub>2</sub>) during the gradual fossil phase-out, as well as the response to historical emissions.”).

<sup>64</sup> Shindell D. & Smith C. J. (2019) [Climate and air-quality benefits of a realistic phase-out of fossil fuels](#), NATURE 573:408–411, Addendum “Methods” (“We note that, although this study focuses on the effects of fossil-fuel related emissions, accounting for the effects of reductions in greenhouse gases from non-fossil sources—including fluorinated gases and both methane and nitrous oxide from agriculture—along with biofuels that are a large source of warming black carbon, could eliminate any near-term penalty entirely. In fact, given that the net effect of the fossil-fuel phase-out on temperature is minimal during the first 20 years (Fig. 3), reducing those other emissions is the only plausible way in which to decrease warming during that period.”). See also Lelieveld J., Klingmüller K., Pozzer A., Burnett R. T., Haines A., & Ramanathan V. (2019) [Effects of fossil fuel and total anthropogenic emission removal on public health and climate](#), PROC. NAT’L. ACAD. SCI. 116(15):7192–7197, 7194 (“Some near-term mitigation can be achieved from the simultaneous reduction of short-lived greenhouse gases such as methane (CH<sub>4</sub>), O<sub>3</sub>, and hydrofluorocarbons (HFCs) (15, 23–25). Fossil-fuel-related CH<sub>4</sub> emissions constitute nearly 20% of the total source, and removing all anthropogenic CH<sub>4</sub> (nearly 60% of the source), in addition to anthropogenic O<sub>3</sub>, would limit the near-term warming to 0.36(±0.06) °C. While the current climate forcing of HFCs is still small, it will be critical to prevent increases in the future, as they are potent greenhouse gases (26). Table 1 presents the unavoidable net warming from emission control measures that simultaneously affect aerosols and greenhouse gases, which have many sources in common. SI Appendix, Table S1 lists these results for all countries, including the uncertainty intervals.”).

<sup>65</sup> Xu Y. & Ramanathan V. (2017) [Well below 2 °C: Mitigation strategies for avoiding dangerous to catastrophic climate changes](#), PROC. NAT’L. ACAD. SCI. 114(39):10315–10323, 10321 (“The SP [super pollutant] lever targets SLCPs. Reducing SLCP emissions thins the SP blanket within few decades, given the shorter lifetimes of SLCPs (weeks for BC to about 15 years for HFCs). The mitigation potential of the SP lever with a maximum deployment of current technologies ... is about 0.6 °C by 2050 and 1.2 °C by 2100 (SI Appendix, Fig. S5B and Table S1).”).

<sup>66</sup> Shindell D., et al. (2012) [Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security](#), SCIENCE 335(6065):183–189, 183–185 (“The global mean response to the CH<sub>4</sub> plus BC measures was  $-0.54 \pm 0.05$ °C in the climate model. ...Roughly half the forcing is relatively evenly distributed (from the CH<sub>4</sub> measures). The other half is highly inhomogeneous, especially the strong BC forcing, which is greatest over bright desert and snow or ice surfaces. Those areas often exhibit the largest warming mitigation, making the regional temperature response to aerosols and ozone quite distinct from the more homogeneous response to well-mixed greenhouse gases... . BC albedo and direct forcings are large in the Himalayas, where there is an especially pronounced response in the Karakoram, and in the Arctic, where the measures reduce projected warming over the next three decades by approximately two thirds and where regional temperature response patterns correspond fairly closely to albedo forcing (for example, they are larger over the Canadian archipelago than the interior and larger over Russia than Scandinavia or the North Atlantic.”). See also United Nations Environment Programme (UNEP) & World Meteorological Organization (WMO) (2011) [Integrated Assessment of Black Carbon and Tropospheric Ozone](#), 262 (“Large impacts of the measures examined here were also seen for the Arctic despite the minimal amount of emissions currently taking place there. This occurs due to the high sensitivity of the Arctic both to pollutants that are transported there from remote sources and to radiative forcing that takes place in areas of the northern hemisphere outside the Arctic. The 16 measures examined here, including the measures on pellet stoves and coal briquettes, reduce warming in the Arctic by 0.7 °C (range 0.2 to 1.3 °C) at 2040. This is a large portion of the 1.1 °C (range 0.7 to 1.7 °C) warming projected under the reference scenario for the Arctic, and hence implementation of the measures would be virtually certain to substantially slow, but not halt, the pace of Arctic climate change.”).

<sup>67</sup> Allen M. R., et al. (2018) [Chapter 1: Framing and Context](#), in Intergovernmental Panel on Climate Change (IPCC) [GLOBAL WARMING OF 1.5 °C](#), y Masson-Delmotte, V. P., et al. (eds.), 61 (“If emission reductions do not begin until temperatures are close to the proposed limit, pathways remaining below 1.5°C necessarily involve much faster rates of net CO<sub>2</sub> emission reductions (Figure 1.4, green lines), combined with rapid reductions in non-CO<sub>2</sub> forcing and these pathways also reach 1.5°C earlier. Note that the emissions associated with these schematic temperature pathways may not correspond to feasible emission scenarios, but they do illustrate the fact that the timing of net zero emissions does not in itself determine peak warming: what matters is total cumulative emissions up to that time. Hence every year’s delay before initiating emission reductions decreases by approximately two years the remaining time available to reach zero emissions on a pathway still remaining below 1.5°C (Allen and Stocker, 2013; Leach et al., 2018).”).

<sup>68</sup> Shindell D. T., Borgford-Parnell N., Brauer M., Haines A., Kuylenskierna J. C. I., Leonard S. A., Ramanathan V., Ravishankara A., Amann M., & Srivastava L. (2017) [A climate policy pathway for near- and long-term benefits](#), SCIENCE 356(6337):493–494.

<sup>69</sup> Ripple W. J., Wolf C., Newsome T. M., Barnard P., & Moomaw W. R. (2019) [World Scientists’ Warning of a Climate Emergency](#), BIOSCIENCE 70(1):8–12.

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<sup>70</sup> Xu Y., Zaelke D., Velders G. J. M., & Ramanathan V. (2013) [The role of HFCs in mitigating 21st century climate change](#), *ATMOS. CHEM. & PHYS.* 13(12):6083–6089, 6083 (“Here we show that avoiding production and use of high-GWP (global warming potential) HFCs by using technologically feasible low-GWP substitutes to meet the increasing global demand can avoid as much as another 0.5 °C warming by the end of the century. This combine mitigation on SLCPs would cut the cumulative warming since 2005 by 50% at 2050 and by 60% at 2100 from the CO<sub>2</sub>-only mitigation scenarios, significantly reducing the rate of warming and lowering the probability of exceeding the 2 °C warming threshold during this century.”).

<sup>71</sup> World Meteorological Organization (WMO), United Nations Environment Programme (UNEP), National Oceanic and Atmospheric Administration (NOAA), National Aeronautics and Space Administration (NASA), & European Commission (2018) [Executive Summary: Scientific Assessment of Ozone Depletion: 2018](#), Global Ozone Research and Monitoring Project-Report No. 58, ES.22 (“The Kigali Amendment is projected to reduce future global average warming in 2100 due to HFCs from a baseline of 0.3-0.5 °C to less than 0.1 °C (Figure ES-4). If the global production of HFCs were to cease in 2020, the surface temperature contribution of the HFC emissions would stay below 0.02 °C for the whole 21st century. The magnitude of the avoided temperature increase, due to the provisions of the Kigali Amendment (0.2 to 0.4 °C) is substantial in the context of the 2015 UNFCCC Paris Agreement, which aims to limit global temperature rise to well below 2.0 °C above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 °C.”); 2.40–2.41 (“With the Kigali Amendment and national and regional regulations, the future production and consumption of HFCs is strongly limited (Table 2-1). Under the provisions of the Amendment, the contribution of HFCs to the global average surface temperature is projected to reach a maximum around 2060, after which it slowly decreases to about 0.06°C by 2100 (Figure 2-20). In contrast, the surface temperature contribution from HFCs in the baseline scenario is 0.3–0.5°C in 2100 (based on Xu et al., 2013 and Velders et al., 2015). The difference in projected temperatures is relevant in the context of the 2015 UNFCCC Paris Agreement, which aims to limit the global temperature increase to well below 2°C relative to pre-industrial levels.”).

<sup>72</sup> World Meteorological Organization (WMO), United Nations Environment Programme (UNEP), National Oceanic and Atmospheric Administration (NOAA), National Aeronautics and Space Administration (NASA), & European Commission (2018) [Executive Summary: Scientific Assessment of Ozone Depletion: 2018](#), Global Ozone Research and Monitoring Project-Report No. 58, ES.39 (“New controls put in place under the Kigali Amendment mandate HFC-23 by-product destruction, to the extent practicable, beginning in 2020. These controls are expected to limit future emissions and thus slow or reverse atmospheric concentration increases of this potent greenhouse gas.”).

<sup>73</sup> Dreyfus G., Borgford-Parnell N., Christensen J., Fahey D. W. Motherway B., Peters T., Piccolotti R., Shah N., & Xu Y. (2020) [Assessment of climate and development benefits of efficient and climate-friendly cooling](#), xii (“Transitioning to high efficiency cooling equipment can more than double the climate benefits of the HFC phasedown in the near-term by reducing emissions of carbon dioxide (CO<sub>2</sub>) and black carbon from the electricity and diesel used to run air conditioners and other cooling equipment. This also will provide significant economic, health, and development co-benefits. ... Robust policies to promote the use of best technologies currently available for efficient and climate-friendly cooling have the potential to reduce climate emissions from the stationary air conditioning and refrigeration sectors by 130–260 GtCO<sub>2</sub>e by 2050, and 210–460 GtCO<sub>2</sub>e by 2060. A quarter of this mitigation is from phasing down HFCs and switching to alternatives with low global warming potential (GWP), while three-quarters is from improving energy efficiency of cooling equipment and reducing electricity demand, which helps achieve a more rapid transition to carbon free electricity worldwide. The mobile air conditioning sector, where energy consumption is expected to nearly triple by 2050, offers significantly more mitigation potential.”). See also Purohit P., Höglund-Isaksson L., Dulac J., Shah N., Wei M., Rafaj P., & Schöpp W. (2020) [Electricity savings and greenhouse gas emission reductions from global phase-down of hydrofluorocarbons](#), *ATMOS. CHEM. AND PHYS.* 20(19): 11305–11327, 11305 (“The combined effect of HFC phase-down, energy efficiency improvement of the stationary cooling technologies, and future changes in the electricity generation fuel mix would prevent between 411 and 631 PgCO<sub>2</sub> equivalent of GHG emissions between 2018 and 2100, thereby making a significant contribution towards keeping the global temperature rise below 2 °C.”).

<sup>74</sup> [The Climate & Clean Air Coalition to Reduce Short-Lived Climate Pollutants](#) (The CCAC identifies solutions to reduce SLCP emissions, conducts relevant scientific research, and promotes policy development. It is the only institution focusing solely on SLCP mitigation, although it does not have any regulatory authority.).

<sup>75</sup> United Nations Environment Programme (UNEP) & World Meteorological Organization (WMO) (2011) [INTEGRATED ASSESSMENT OF BLACK CARBON AND TROPOSPHERIC OZONE](#), 193, 201 (“Implementing all measures could avoid 2.4 million premature deaths (within a range of 0.7–4.6 million) associated with reductions in PM<sub>2.5</sub>, associated with 5.3–37.4 million years of life lost (YLL), based on the 2030 population.”); “Total global production gains of all crops ranges between 30 and



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140 million tonnes (model mean: 52 million tonnes). The annual economic gains for all four crops in all regions ranges between US\$4 billion and US\$33 billion, of which US\$2–28 billion in Asia.”).

<sup>76</sup> California Air Resources Board (CARB) (2017) [How California is Giving Soot the Boot!](#), Research Synthesis #17-01 (“California’s clean air rules reduced black carbon emissions by 90% since the 1960s, providing immediate climate and health benefits. Ongoing efforts will cut the remaining amount in half by 2030.”).

<sup>77</sup> Sand M., Berntsen T. K., Seland Ø., & Kristjánsson J. E. (2013) [Arctic surface temperature change to emissions of black carbon within Arctic or midlatitudes](#), J. GEOPHYS. RSCH. 118(14):7788–7798, 7788 (“The climate model includes a snow model to simulate the climate effect of BC deposited on snow. We find that BC emitted within the Arctic has an almost five times larger Arctic surface temperature response (per unit of emitted mass) compared to emissions at midlatitudes. Especially during winter, BC emitted in North-Eurasia is transported into the high Arctic at low altitudes. A large fraction of the surface temperature response from BC is due to increased absorption when BC is deposited on snow and sea ice with associated feedbacks.”). See also Stohl A., Klimont Z., Eckhardt S., Kupiainen K., Shevchenko V. P., Kopeikin V. M., & Novigatsky A. N. (2013) [Black carbon in the Arctic: the underestimated role of gas flaring and residential combustion emissions](#), ATMOS. CHEM. PHYS. 13(17):8833–8855, 8848 (Fig. 9. Time series of measured EBC and carbon monoxide as well as modeled BC split into different source categories for the Zeppelin station for the period 12 February until 4 March 2010.).

<sup>78</sup> Qian Y., et al. (2014) [Light-absorbing Particles in Snow and Ice: Measurement and Modeling of Climatic and Hydrological Impact](#), ADV. ATMOS. SCI. 32:64–91, 64 (“Light absorbing particles (LAP, e.g., black carbon, brown carbon, and dust) influence water and energy budgets of the atmosphere and snowpack in multiple ways. In addition to their effects associated with atmospheric heating by absorption of solar radiation and interactions with clouds, LAP in snow on land and ice can reduce the surface reflectance (a.k.a., surface darkening), which is likely to accelerate the snow aging process and further reduces snow albedo and increases the speed of snowpack melt. LAP in snow and ice (LAPSI) has been identified as one of major forcings affecting climate change, e.g. in the fourth and fifth assessment reports of IPCC. However, the uncertainty level in quantifying this effect remains very high. In this review paper, we document various technical methods of measuring LAPSI and review the progress made in measuring the LAPSI in Arctic, Tibetan Plateau and other mid-latitude regions. We also report the progress in modeling the mass concentrations, albedo reduction, radiative forcing, and climatic and hydrological impact of LAPSI at global and regional scales. Finally we identify some research needs for reducing the uncertainties in the impact of LAPSI on global and regional climate and the hydrological cycle.”). See also Arctic Monitoring and Assessment Programme (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).”); and 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.”).

<sup>79</sup> International Council on Clean Transport (2020). [The International Maritime Organization’s proposed arctic heavy fuel oil ban: likely impacts and opportunities for improvement](#), 1 (“In February 2020, delegates at the seventh session of the United Nations International Maritime Organization’s (IMO) Pollution Prevention and Response Sub-Committee (PPR 7) agreed on draft amendments to the International Convention for the Prevention of Pollution from Ships (MARPOL) that would ban the carriage and use of heavy fuel oil (HFO) as fuel in Arctic waters beginning on July 1, 2024 (IMO Secretariat, 2020). If it were comprehensive, such a ban would dramatically reduce the potential for HFO spills and, in the likely cases where ships that stop using HFO switch to distillates, reduce the amount of black carbon (BC) they emit (Comer, Olmer, Mao, Roy, & Rutherford, 2017a). However, the text of the ban as currently proposed includes exemptions and waivers that would allow HFO to be carried and used in the Arctic until 2029. As proposed, the ban would enter into force for some ships

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on July 1, 2024, and implementation would be delayed for others. Ships with certain fuel tank protections, where the fuel tank is separated from the outer hull of the ship by at least 76 centimeters (cm), would be exempt until July 1, 2029. Additionally, countries with a coastline that borders IMO's definition of Arctic waters can waive the HFO ban's requirements until July 1, 2029 for ships that fly their flag when those ships are in waters subject to their sovereignty or jurisdiction."'). See also C. Farand (3 September 2020) [Loopholes in Arctic heavy fuel oil ban defer action to the end of the decade](#), *Climate Home News* ("Under draft plans being negotiated at the International Maritime Organisation (IMO) – the UN body responsible for international shipping – restrictions on heavy fuel oil (HFO), a dirty fuel which propels most of marine transport, would come into effect in July 2024. But a host of exemptions and waivers would allow most ships using and carrying HFO to continue to pollute Arctic waters until 2029."').

<sup>80</sup> International Council on Clean Transport (2020) [The International Maritime Organization's proposed arctic heavy fuel oil ban: likely impacts and opportunities for improvement](#), 2–3 ("HFO has already been banned in the Antarctic since 2011, without any exemptions or waivers. In the Antarctic, defined by the IMO's MARPOL Convention as a neat circle below 60°S latitude, ships are not only forbidden from using HFO and carrying HFO in their fuel tanks, they cannot even carry HFO as cargo or ballast. There is little commercial shipping activity in the Antarctic region, and this made the decision less contentious. The Arctic, meanwhile, has substantial amounts of commercial shipping activity, including fishing and the transport of oil, gas, and minerals from the region. The carriage and use of HFO is especially common for oil tankers, general cargo ships, and bulk carriers in the region, as we will show later in this analysis. The Arctic HFO ban, as currently proposed, would start to apply on July 1, 2024 and would forbid using or carrying HFO as fuel, but would allow HFO cargoes to be transported. In addition to the cargo exemption, the text of the HFO ban allows for exemptions and waivers, as follows."'). See also C. Farand (3 September 2020) [Loopholes in Arctic heavy fuel oil ban defer action to the end of the decade](#), *Climate Home News* ("Burning and carrying HFO has been banned in Antarctic waters since 2011, but plans for similar restrictions in the resource-rich Arctic have met with resistance. Russia, which could benefit from the opening of more shipping routes in the region as Arctic sea ice melts, is one of the most vocal opponents."').

<sup>81</sup> International Council on Clean Transport (2020) [The International Maritime Organization's proposed arctic heavy fuel oil ban: likely impacts and opportunities for improvement](#), 10–11, 19 ("As shown in Figure 8, had the proposed HFO ban been in place in 2019, it would have banned just 30% of HFO carried as fuel and 16% of the HFO used by ships in the Arctic. Total BC emissions in the Arctic would have fallen by only 5% because the majority of HFO use would have been allowed by virtue of exemptions or waivers. Of the 700 HFO-fueled ships in the Arctic in 2019, 151, or 22% of the fleet, would have been exempt. Of these, 18 would have been eligible for a waiver had they not already been exempt. The flag state with the most exempt ships was Panama, with 31 ships, followed by Marshall Islands with 27, Liberia with 15, Russia with 11, and the Netherlands with 11. Other flag states had fewer than 10 ships exempt. An additional 366 ships, or 52% of the HFO-fueled fleet, would have been eligible for a waiver, including 325 ships flagged to Russia, 20 to Canada, 10 to Norway, 10 to Denmark, and one to the United States. Together, exemptions and waivers would have allowed 74% of the HFO-fueled fleet, by number of ships, to continue to use HFO in the Arctic."').

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

<sup>83</sup> Climate & Clean Air Coalition (CCAC), [Black Carbon](#) (last visited 08 February 2021) (Listing solutions to reach 70% reduction in black carbon by 2030).

<sup>84</sup> The World Bank (2014) [REDUCING BLACK CARBON EMISSIONS FROM DIESEL VEHICLES: IMPACTS, CONTROL STRATEGIES, AND COST-BENEFIT ANALYSIS](#), 17 ("A vehicle emissions reduction program often focuses on three areas: new vehicles, fuels, and the in-use fleet. In some countries it may make sense to start with the in-use fleet and transportation demand management. In certain cases, fiscal policies can be effective tools to complement mandatory regulatory requirements. The order or priority in approach should be dictated by the baseline technology, the rate of growth of the fleet, the feasibility of available options,

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the institutional capacity to support the intervention, and other local considerations. Successful strategies tend to take a holistic approach that integrates all maximum feasible and cost-effective emissions reduction strategies.”). *See also* Bond T.C., *et al.* (2013) [Bounding the role of black carbon in the climate system: A scientific assessment](#), *J. GEOPHYS. RSCH. ATMOSPHERES* 118(11):5380–5552, 5525 (“Diesel sources of BC appear to offer the most promising mitigation opportunities in terms of near-term forcing and maturity of technology and delivery programs. Although some options, such as diesel retrofits, may be costly relative to other BC mitigation options, they may also deliver significant health benefits. Mitigating emissions from residential solid fuels may yield a reduction in net positive forcing. The near-term net effect remains uncertain because of uncertain knowledge regarding the impacts of co-emitted species on clouds, but longer-term forcing by co-emitted species interacting with the methane budget is positive. Furthermore, the evolution of feasibility is still in the emerging phase for these sources.”).

<sup>85</sup> Clean Air Task Force (CATF), [Oil and Gas Mitigation Program](#) (*last visited* 05 February 2021) (Operators often vent and flare natural gas at oil wells. This waste occurs when oil producers, driven by the rush to sell oil, simply dispose of the gas from producing oil wells instead of building infrastructure (such as pipelines) to capture gas as soon as production begins. (In some cases, pipelines are never built and all of the gas the well produces over its lifetime is wasted in this way, as can be seen in sales records for individual wells available from state regulators.) While a substantial portion of this gas is flared off—wasting energy and producing large amounts of carbon dioxide and other pollutants—some is just dumped into the air, or vented. Even in cases where a gas pipeline is not connected, there are a variety of other [technologies](#) that operators can use to reduce associated gas flaring at oil wells. Venting is even more harmful than flaring, since methane warms the climate so powerfully, and VOC and toxic pollutants are released unabated. Venting of this gas should be prohibited in all cases as an absolutely unnecessary source of harmful air pollution. There are numerous lowcost (and usually profitable) ways to utilize natural gas from oil wells. Flaring should be a last resort: only in the most extreme cases should oil producers be allowed to flare gas, and it should be strictly a temporary measure. Rules prohibiting venting of natural gas can easily reduce emissions by 95 percent.”). *See also* The World Bank, [Zero Routine Flaring by 2030](#) (*Last visited* 4 February 2021) (“This “**Zero Routine Flaring by 2030**” initiative (the Initiative), introduced by the World Bank, brings together governments, oil companies, and development institutions who recognize the flaring situation described above is unsustainable from a resource management and environmental perspective, and who agree to cooperate to eliminate routine flaring no later than 2030.”); and Saunier S., Bergauer M-A., & Isakova I. (2019) [Best Available Techniques Economically Achievable to Address Black Carbon from Gas Flaring](#); EU Action on Black Carbon in the Arctic - Technical Report 3 (“Although the effectiveness of BATEA largely depends on site-specific economic and technical parameters, they have a substantial potential to achieve meaningful and measurable environmental and financial benefits. Quantifying resultant reductions in BC emissions as a result of mitigation strategies remains challenging, however, implementing BATEA should still be considered a best practice for reducing flaring-associated BC emissions. Along with other newly available technologies, use of the BATEA described herein will support existing efforts to mitigate short-term climate change, as well as address other energy, environmental, and safety issues that are likely to result from gas flaring in Arctic regions.”).

<sup>86</sup> International Energy Agency (IEA), International Renewable Energy Agency (IRENA), United Nations Statistics Division (UNSD), World Bank, & World Health Organization (WHO) (2020) [TRACKING SDG 7: THE ENERGY PROGRESS REPORT](#), WORLD BANK, 6 (“The share of the global population with access to clean fuels and technologies for cooking increased from 56 percent in 2010 (uncertainty interval 52–61 percent) to 63 percent in 2018 (56–68), leaving approximately 2.8 billion people without access.<sup>1</sup> That number has been largely unchanged over the past two decades owing to population growth outpacing the number of people gaining access to clean cooking solutions.”). Cleaner cookstoves must also be reliable for interventions to succeed. *See* Ramanathan T., Molin Valdés H., & Coldrey O. (07 September 2020) [Reliability matters: Achieving affordable, reliable, sustainable and modern energy for all by 2030](#), *Sustainable Energy for All* (“A cooking solution (improved biomass, gas, electric, etc.) is reliable when it offers a household the predictable ability to cleanly cook essential foods on a daily basis and to continue to do so into the foreseeable future. Reliability is a holistic concept that encompasses not only the verifiability of emissions reduction, but also accounts for end users’ needs (e.g. usability of design, long-term durability, affordability, and strength of supply chain). Compromising any of those factors can mean that even if a cooking solution is perceived as beneficial, it may not be well suited and will therefore ultimately not meet its targeted goal of cleaner air.”).

<sup>87</sup> Comer B., Osipova L., Georgeff E., & Mao X. (2020) [The International Maritime Organization’s proposed arctic heavy fuel oil ban: likely impacts and opportunities for improvement](#), International Council on Clean Transport (ICCT), 1 (“In February 2020, delegates at the seventh session of the United Nations International Maritime Organization’s (IMO) Pollution Prevention and Response Sub-Committee (PPR 7) agreed on draft amendments to the International Convention for the Prevention of Pollution from Ships (MARPOL) that would ban the carriage and use of heavy fuel oil (HFO) as fuel in Arctic waters beginning on July 1, 2024 (IMO Secretariat, 2020). If it were comprehensive, such a ban would dramatically reduce the potential for HFO spills and, in the likely cases where ships that stop using HFO switch to distillates, reduce the amount

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of black carbon (BC) they emit (Comer, Olmer, Mao, Roy, & Rutherford, 2017a). However, the text of the ban as currently proposed includes exemptions and waivers that would allow HFO to be carried and used in the Arctic until 2029. As proposed, the ban would enter into force for some ships on July 1, 2024, and implementation would be delayed for others. Ships with certain fuel tank protections, where the fuel tank is separated from the outer hull of the ship by at least 76 centimeters (cm), would be exempt until July 1, 2029. Additionally, countries with a coastline that borders IMO's definition of Arctic waters can waive the HFO ban's requirements until July 1, 2029 for ships that fly their flag when those ships are in waters subject to their sovereignty or jurisdiction." See also C. Farand (3 September 2020) [Loopholes in Arctic heavy fuel oil ban defer action to the end of the decade](#), *Climate Home News* ("Under draft plans being negotiated at the International Maritime Organisation (IMO) – the UN body responsible for international shipping – restrictions on heavy fuel oil (HFO), a dirty fuel which propels most of marine transport, would come into effect in July 2024. But a host of exemptions and waivers would allow most ships using and carrying HFO to continue to pollute Arctic waters until 2029.").

<sup>88</sup> 1999 Protocol to Abate Acidification, Eutrophication and Ground-Level Ozone (Gothenburg Protocol), [Decision 2012/8](#): Adoption of guidance document on control techniques for emissions of sulphur, nitrogen oxides, volatile organic compounds and particulate matter (including PM<sub>10</sub>, PM<sub>2.5</sub>, and black carbon) from stationary sources. See also Matthews B. & Paunu V-V. (2019) [Review of Reporting Systems for National Black Carbon Emissions Inventories: EU Action on Black Carbon in the Arctic - Technical Report](#), 1–2 ("Emissions reporting systems are thus in need of further improvement. In evaluating needs for improvement, the EU Action on Black Carbon in the Arctic review identified the following priority areas . . . 4. Enhanced cooperation between CLRTAP and the Arctic Council to expand and harmonise black carbon emissions reporting by countries whose black carbon emissions impact the Arctic."). Compare Expert Group on Black Carbon and Methane (2019) [Summary of Progress and Recommendations](#), Arctic Council Secretariat, 32, tbl. 5 (Showing US with 9.5bcm of flaring based on World Bank satellite observations); with EIA, [Flaring and Venting Data](#) (last visited 05 February 2021) (showing combined flaring and venting volumes of 255bcf for 2017).

<sup>89</sup> European Commission (14 October 2020) [Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on an EU Strategy to Reduce Methane Emissions](#), 1 ("At a global level, reducing methane emissions associated with human (anthropogenic) activity by 50% over the next 30 years could reduce global temperature change by 0.18 degrees Celsius by 2050.")

<sup>90</sup> [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.").

<sup>91</sup> United States Climate Alliance (2018) [From SLCP Challenge to Action: A roadmap for reducing short-lived climate pollutants to meet the goals of the Paris Agreement](#), 11 ("Significant additional opportunities exist to cut methane emissions quickly and cost effectively across the U.S. Capturing the full potential of expected reduction opportunities, as described in Appendix A, could reduce methane emissions by 40-50 percent below current levels in the U.S. Climate Alliance. Existing and emerging strategies and technologies can achieve these reductions by 2030.").

<sup>92</sup> United States Climate Alliance (2018) [From SLCP Challenge to Action: A roadmap for reducing short-lived climate pollutants to meet the goals of the Paris Agreement](#), 11 ("There is an opportunity for the U.S. Climate Alliance to help fulfill the commitment by the U.S., Canada, and Mexico to implement federal regulations on new and existing sources in the oil and gas sector to reduce methane emissions by 40-45 percent below 2012 levels by 2025."). In 2016, the U.S., Canada, and Mexico committed to reducing methane emissions in the oil and gas sector by 40–45% by 2025 (compared to 2012 levels). See Canada, Mexico, & United States of America (2016) [Leaders' Statement on a North American Climate, Clean Energy, and Environment Partnership](#), 2 ("Today, Mexico will join Canada and the United States in committing to reduce their methane emissions from the oil and gas sector – the world's largest methane source – 40% to 45% by 2025, towards achieving the greenhouse gas targets in our nationally determined contributions. To achieve this goal, the three countries commit to develop and implement federal regulations to reduce emissions from existing and new sources in the oil and gas sector as soon as possible. We also commit to develop and implement national methane reduction strategies for key sectors such as oil and gas, agriculture, and waste management, including food waste.").

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<sup>93</sup> United States Climate Alliance (2018) [From SLCP Challenge to Action: A roadmap for reducing short-lived climate pollutants to meet the goals of the Paris Agreement](#), 15 (“Significant opportunities for reducing methane emissions from landfills and capturing value can be seized by reducing food loss and waste, diverting organic waste to beneficial uses, and improving landfill management. These and other actions collectively could reduce methane emissions from waste by an estimated 40-50 percent by 2030 (Appendix A). Such efforts could add value in our states by reducing emissions of volatile organic compounds and toxic air contaminants from landfills, recovering healthy food for human consumption in food insecure communities, supporting healthy soils and agriculture, generating clean energy and displacing fossil fuel consumption, and providing economic opportunities across these diverse sectors. Many of these benefits will accrue in low-income and disadvantaged communities.”).

<sup>94</sup> United States Climate Alliance (2018) [From SLCP Challenge to Action: A roadmap for reducing short-lived climate pollutants to meet the goals of the Paris Agreement](#), 13 (“Actions to improve manure management and to reduce methane from enteric fermentation have the potential to significantly reduce agricultural methane emissions across U.S. Climate Alliance states . . . . Promising technologies are also emerging that may cut methane emissions from enteric fermentation by 30 percent or more (Appendix A). Developing strategies that work for farmers and surrounding communities can significantly reduce methane emissions, increase and diversify farm revenues, and support water quality and other environmental benefits.”). See also Ross E. G., et al. (2020) [Effect of SOP "STAR COW" on Enteric Gaseous Emissions and Dairy Cattle Performance](#), SUSTAINABILITY 12(24): 1–12, 1 (“The aim of this study was to investigate the efficacy of the commercial feed additive SOP STAR COW (SOP) to reduce enteric emissions from dairy cows and to assess potential impacts on milk production. . . . SOP-treated cows over time showed a reduction in CH<sub>4</sub> of 20.4% from day 14 to day 42 ( $p = 0.014$ ), while protein % of the milk was increased (+4.9% from day 0 to day 14 ( $p = 0.036$ ) and +6.5% from day 0 to day 42 ( $p = 0.002$ )).”).

<sup>95</sup> United States Climate Alliance (2018) [From SLCP Challenge to Action: A roadmap for reducing short-lived climate pollutants to meet the goals of the Paris Agreement](#), 13 (“Actions to improve manure management and to reduce methane from enteric fermentation have the potential to significantly reduce agricultural methane emissions across U.S. Climate Alliance states. Improving manure storage and handling, composting manure, utilizing pasture-based systems, or installing anaerobic digesters significantly reduces methane from manure management on dairy, swine, and other livestock operations. These practices may reduce methane from manure management by as much as 70 percent in U.S. Climate Alliance states (Appendix A) and can help improve soil quality and fertility, reduce water use and increase water quality, reduce odors, and decrease the need for synthetic fertilizers and associated greenhouse gas emissions . . . . Developing strategies that work for farmers and surrounding communities can significantly reduce methane emissions, increase and diversify farm revenues, and support water quality and other environmental benefits.”). See also Borgonovo F., et al. (2019) [Improving the Sustainability of Dairy Slurry with a Commercial Additive Treatment](#), SUSTAINABILITY 11(18):1–14, 8 (claiming that additives treating liquid manure of dairy cows, made from agricultural gypsum processed with proprietary technology [SOP LAGOON], showed significant reductions of climate emissions from waste slurry, eliminating ammonia and N<sub>2</sub>O, and significantly reducing CH<sub>4</sub> and CO<sub>2</sub>. “N<sub>2</sub>O, CO<sub>2</sub>, and CH<sub>4</sub> emissions, from the treated slurry, were respectively 100%, 22.9% and 21.5% lower than the control at T4 [Day 4] when the emission peaks were recorded.”).

<sup>96</sup> White House Office of the Press Secretary, [Leaders' Statement on a North American Climate, Clean Energy, and Environment Partnership](#) (29 June 2016) (“Today, Mexico will join Canada and the United States in committing to reduce their methane emissions from the oil and gas sector – the world’s largest industrial methane source – 40% to 45% by 2025, towards achieving the greenhouse gas targets in our nationally determined contributions. To achieve this goal, the three countries commit to develop and implement federal regulations to reduce emissions from existing and new sources in the oil and gas sector as soon as possible. We also commit to develop and implement national methane reduction strategies for key sectors such as oil and gas, agriculture, and waste management, including food waste.”). See also White House Office of the Press Secretary, [North American Climate, Clean Energy, and Environment Partnership Action Plan](#) (29 June 2016) (“Reduce methane emissions from the oil and gas sector, the world’s largest industrial methane source, 40-45% by 2025 towards achieving the greenhouse gas targets in our nationally determined contributions, and explore additional opportunities for methane reductions. The three countries commit to develop and implement federal regulations for both existing and new sources as soon as possible to achieve the target. We intend to invite other countries to join this ambitious target or develop their own methane reduction goal.”).

<sup>97</sup> European Commission (17 September 2020) COM/2020/562: [Stepping up Europe's 2030 Climate Ambition, Investing in a Climate Neutral Future for the Benefit of our People](#), 2 (“The present Communication therefore: 1. Presents an EU-wide, economy-wide greenhouse gas emissions reduction target by 2030 compared to 1990 of at least 55% including emissions and removals. The EU is implementing its current 2030 climate target of at least 40% greenhouse gas emissions reductions through three key pieces of climate legislation.”).

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<sup>98</sup> European Commission (14 October 2020) COM/2020/663: [Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee, and the Committee of the Regions on an EU Strategy to Reduce Methane Emissions](#), 2 (“Nevertheless, the 2030 climate target plan’s impact assessment found methane will continue to be the EU’s dominant non-CO<sub>2</sub> greenhouse<sup>7</sup>. It concluded that stepping up the level of ambition for reductions in greenhousegas emissions to at least 55% by 2030 compared to 1990 would also require an accelerated effort to tackle methane emissions, with projections indicating a step up needed to 35% to 37% methane emission reductions by 2030 compared to 2005.”).

<sup>99</sup> European Commission (14 October 2020) COM/2020/663: [Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee, and the Committee of the Regions on an EU Strategy to Reduce Methane Emissions](#), 13 (“In line with the 2030 Climate Target Plan the Effort Sharing Regulation (ESR) (which covers methane emissions from agriculture), will now be reviewed to reflect the increased carbon reduction target providing for increased incentives to reduce methane emissions.”).

<sup>100</sup> European Commission (14 October 2020) COM/2020/663: [Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee, and the Committee of the Regions on an EU Strategy to Reduce Methane Emissions](#), 7 (“The Commission will also review the National Emission Reduction Commitments (NEC) Directive by 2025 and, as part of this review, explore the possible inclusion of methane among the regulated pollutants.”).

<sup>101</sup> van Dingenen R., Crippa M., Maenhout G., Guizzardi D., & Dentener F. (2018) [Global trends of methane emissions and their impacts on ozone concentrations](#), Publications of the Office of the European Union, 47 (“The relevance of CH<sub>4</sub> mitigation efforts can be put in perspective applying its global warming potential of 28 (Myhre et al., 2013) to evaluate the CO<sub>2</sub>e emissions. Relative to the year 2010, the most stringent emission scenarios (i.e. MTR or a 2° scenario) lead to a CO<sub>2</sub>e emission reduction of 2.4 to 3.7 Gt annually in 2030 and 2.9 to 5.1 Gt in 2050 whereas the high emission scenarios lead to an emission increase of 1.6 to 3.6 Gt CO<sub>2</sub>e in 2030 (3.1 to 8.6 Gt in 2050). The UNEP Emission Gap Report 2017 ([UNEP, 2017](#)) indicates that, in order to meet the year 2100 2° target, by 2030, additionally to the NDCs 11 to 13.5 GtCO<sub>2</sub>e emission reductions have to be achieved. The stringent emission control scenarios in our analysis foresee a reduction of -2 to -4 GtCO<sub>2</sub>e relative to the GECO INDC scenario by 2030, hence contributing 15 to 33% to the required emission gap closure. In contrast, under non-ambitious CH<sub>4</sub> mitigation scenarios, the total mitigation effort needed for reducing emissions of other GHGs would increase by 2 to 4Gt CO<sub>2</sub>e.”).

<sup>102</sup> Climate & Clean Air Coalition (CCAC), [A Global Alliance to Significantly Reduce Methane Emissions in the Oil and Gas Sector by 2030](#) (last accessed 05 February 2021) (“Absolute reduction target of at least 45% reduction in methane emissions by 2025 and 60% to 75% by 2030 . . . are realistic and achievable targets, especially in a sector where technology and financing are largely available, and innovation supports even larger reductions . . . Reductions across the oil and gas industry in line with the Global Methane Alliance could reduce global emissions by 6 gigatons CO<sub>2</sub>e by 2030. According to the [UNEP Emissions Gap Report 2019](#), this would achieve between 20%-50% of the emissions required to limit climate warming to 2-degrees.”). See also Nisbet E. G., et al. (2020) [Methane Mitigation: Methods to Reduce Emissions, on the Path to the Paris Agreement](#), REV. GEOPHYS. 58:e2019RG000675, 1–51, 1 (“Many methane mitigation options offer cost-effective approaches to cut global warming and bring the amount of methane in the air back to a pathway that is consistent with the aims of the Paris Agreement.”).

<sup>103</sup> Clean Air Task Force (CATF), [Oil and Gas Mitigation Program](#) (last visited 5 February 2021) (“Compared to other climate change solutions, methane mitigation from the oil and gas sector is relatively cheap. Some measures actually save money, when the extra revenue from selling gas that would otherwise be released into the air is factored in. The [International Energy Agency \(IEA\)](#) estimates that globally, a 75% reduction in oil and gas methane is possible with today’s technology, and a 50% reduction is possible at no net cost. Just a 50% cut would have the same long-term climate impact as closing all the coal plants in China. Many national and sub-national governments have already moved forward with strong oil and gas methane regulations that require mitigation from some or all of these sources. Some of the strongest current regulations can be found in [Canada](#), [Colorado](#), [California](#), and [Mexico](#).”). See also United Nations Environment Programme (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.”).

<sup>104</sup> Jackson R. B., et al. (2020) [Increasing anthropogenic methane emissions arise equally from agricultural and fossil fuel sources](#), ENV’T RSCH. LETT. 15(071002):1–7, 6 (“Increased emissions from both the agriculture and waste sector and the

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

<sup>105</sup> Clean Air Task Force (CATF), [Oil and Gas Mitigation Program](#) (*last visited* 5 February 2021) (“Fortunately, most leaks are straightforward to repair (and [fixing leaks is paid for by the value of the gas that is saved by repairing them](#)). Further, finding leaks has become efficient with modern technology. The standard approach today is to use special cameras that can detect infrared light (think of night-vision goggles) which are tuned to make methane, which is invisible to our eyes, visible. They allow inspectors to directly image leaking gas in real time, with the ability to inspect entire components (not just connections and other areas most likely to leak) and pinpoint the precise source, making repair more straightforward. And, technology promises to make this process [even more efficient \(and cheaper\) over the coming years](#). These technologies can be utilized to reduce harmful leak emissions, by using regular inspections as the lynchpin of rigorous “leak detection and repair” (LDAR) programs. These programs require operators to regularly survey all of their facilities for leaks and improper emissions, and repair all the leaks they identify in a reasonable time. For example, [California](#) requires operators to survey all sites four times a year. [Colorado](#) has a different approach, requiring operators of the largest sites to survey them monthly, but requiring less frequent inspections for site with smaller potential emissions.”).

<sup>106</sup> Clean Air Task Force (CATF), [Oil and Gas Mitigation Program](#) (*last visited* 5 February 2021) (Listing pneumatic equipment venting, compressor seal venting, tank venting, well completion venting, oil well venting and flaring, and dehydrator venting as sources of the “biggest mitigation opportunities.”).

<sup>107</sup> Clean Air Task Force (CATF), [Oil and Gas Mitigation Program](#) (*last visited* 5 February 2021) (“Venting is even more harmful than flaring, since methane warms the climate so powerfully, and VOC and toxic pollutants are released unabated. Venting of this gas should be prohibited in all cases as an absolutely unnecessary source of harmful air pollution. There are numerous lowcost (and usually profitable) ways to utilize natural gas from oil wells. Flaring should be a last resort: only in the most extreme cases should oil producers be allowed to flare gas, and it should be strictly a temporary measure. Rules prohibiting venting of natural gas can easily reduce emissions by 95 percent.”).

<sup>108</sup> Clean Air Task Force (CATF), [Oil and Gas Mitigation Program](#) (*last visited* 5 February 2021) (“Operators often vent and flare natural gas at oil wells. This waste occurs when oil producers, driven by the rush to sell oil, simply dispose of the gas from producing oil wells instead of building infrastructure (such as pipelines) to capture gas as soon as production begins. (In some cases, pipelines are never built and all of the gas the well produces over its lifetime is wasted in this way, as can be seen in sales records for individual wells available from state regulators.) While a substantial portion of this gas is flared off—wasting energy and producing large amounts of carbon dioxide and other pollutants—some is just dumped into the air, or vented. Even in cases where a gas pipeline is not connected, there are a variety of other [technologies](#) that operators can use to reduce associated gas flaring at oil wells. Venting is even more harmful than flaring, since methane warms the climate so powerfully, and VOC and toxic pollutants are released unabated. Venting of this gas should be prohibited in all cases as an absolutely unnecessary source of harmful air pollution. There are numerous lowcost (and usually profitable) ways to utilize natural gas from oil wells. Flaring should be a last resort: only in the most extreme cases should oil producers be allowed to flare gas, and it should be strictly a temporary measure. Rules prohibiting venting of natural gas can easily reduce emissions by 95 percent.”). *See also* The World Bank, [Zero Routine Flaring by 2030](#) (*last visited* 4 February 2021) (“This “**Zero Routine Flaring by 2030**” initiative (the Initiative), introduced by the World Bank, brings together governments, oil companies, and development institutions who recognize the flaring situation described above is unsustainable from a resource management and environmental perspective, and who agree to cooperate to eliminate routine flaring no later than 2030.”).

<sup>109</sup> United States Climate Alliance, (2018) [From SLCPC Challenge to Action: A roadmap for reducing short-lived climate pollutants to meet the goals of the Paris Agreement](#), 13 (“Actions to improve manure management and to reduce methane from enteric fermentation have the potential to significantly reduce agricultural methane emissions across U.S. Climate Alliance states. Improving manure storage and handling, composting manure, utilizing pasture-based systems, or installing anaerobic digesters significantly reduces methane from manure management on dairy, swine, and other livestock operations. These practices may reduce methane from manure management by as much as 70 percent in U.S. Climate Alliance states (Appendix A) and can help improve soil quality and fertility, reduce water use and increase water quality, reduce odors, and decrease the need for synthetic fertilizers and associated greenhouse gas emissions. Promising technologies are also emerging

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that may cut methane emissions from enteric fermentation by 30 percent or more (Appendix A). Developing strategies that work for farmers and surrounding communities can significantly reduce methane emissions, increase and diversify farm revenues, and support water quality and other environmental benefits.”). See also Höglund-Isaksson L., et al. (2020) [\*Technical potentials and costs for reducing global anthropogenic methane emissions in the 2050 timeframe—results from the GAINS model\*](#), ENV’T RSCH. COMM. 2(025004):1–21, 13–14 (“The technical abatement potential for agricultural sources is assessed at 21 percent below baseline emissions in year 2050. This includes relatively limited abatement potentials for livestock of 12 percent due to applicability limitations (see section S3.4. in the SI for details). Large farms with more than 100 LSU contribute about a third of global CH<sub>4</sub> emissions from livestock and for this group we find it technically feasible to reduce emissions by just over 30 percent below baseline emissions in year 2050 (see figures S6–2 in the SI). The available options include reduction of enteric fermentation emissions through animal feed changes (Gerber et al 2013, Hristov et al 2013) combined with implementation of breeding schemes that simultaneously target genetic traits for improved productivity and enhanced animal health/longevity and fertility. Increased productivity reduces system emissions by enabling the production of the same amount of milk using fewer animals. The dual objective in breeding schemes is important as a one-eyed focus on increased productivity leads to deteriorating animal health and fertility and a risk that system emissions increase due to a need to keep a larger fraction of unproductive replacement animals in the stock (Lovett et al 2006, Berglund 2008, Bell et al 2011). The enteric fermentation options are considered economically feasible for commercial/industrial farms with more than 100 LSU but not for smaller- and medium- sized farms. Breeding schemes are assumed to deliver impacts on emissions only after 20 years and feed changes are assumed applicable only while animals are housed indoor. Emissions from manure management can be reduced through treatment of manure in anaerobic digesters (ADs) with biogas recovery. To be efficient from both an economic and environmental point of view, a certain scale is needed to accommodate both the fixed investment of the AD plant and the time farmers spend carefully attending to and maintaining the process (for details see section 3.3.1.3 in Höglund-Isaksson et al 2018).”) and Borgonovo F., et al. (2019) [\*Improving the sustainability of dairy slurry with a commercial additive treatment\*](#), SUSTAINABILITY 11(4988): 1–14, 8 (“N<sub>2</sub>O, CO<sub>2</sub>, and CH<sub>4</sub> emissions, from the treated slurry, were respectively 100%, 22.9% and 21.5% lower than the control at T4 when the emission peaks were recorded.”).

<sup>110</sup> Höglund-Isaksson L., Gómez-Sanabria, A., Zbigniew, K., Rafaj, P., & Schöpp, W. (2020) [\*Technical potentials and costs for reducing global anthropogenic methane emissions in the 2050 timeframe—results from the GAINS model\*](#), ENV’T RSCH. COMM. 2(025004):1–21, 16–17 (“An additional almost 10 percent of baseline emissions in 2050 could be removed at a marginal cost below 20 €/t CO<sub>2</sub>eq by implementing proper waste and wastewater handling in China, India and the rest of South-East Asia. This would likely come with considerable co-benefits in the form of reduced air and water pollution.”).

<sup>111</sup> United States Climate Alliance (2018) [\*From SLCP Challenge to Action: A roadmap for reducing short-lived climate pollutants to meet the goals of the Paris Agreement\*](#), 15 (“Significant opportunities for reducing methane emissions from landfills and capturing value can be seized by reducing food loss and waste, diverting organic waste to beneficial uses, and improving landfill management. These and other actions collectively could reduce methane emissions from waste by an estimated 40-50 percent by 2030 (Appendix A). Such efforts could add value in our states by reducing emissions of volatile organic compounds and toxic air contaminants from landfills, recovering healthy food for human consumption in food insecure communities, supporting healthy soils and agriculture, generating clean energy and displacing fossil fuel consumption, and providing economic opportunities across these diverse sectors. Many of these benefits will accrue in low-income and disadvantaged communities.”).

<sup>112</sup> Portmann, R.W., Daniel, J.S., & Ravishankara, A.R. (2012) [\*Stratospheric Ozone Depletion Due to Nitrous Oxide: Influences of Other Gases\*](#), PHILOS. TRANSACTIONS OF THE ROYAL SOC’Y 367:1256–1264, 1262 (“By 2008, anthropogenic N<sub>2</sub>O was the most significant ozone-destroying compound being emitted. Owing to the phase-out of anthropogenic halocarbon emissions, it is likely to become even more dominant in the near future.”). See also Porter, I. (2019) [\*Mitigation of Nitrous Oxide Emissions\*](#) (presentation at 31<sup>st</sup> Meeting of the Parties to the Montreal Protocol) (“By 2050, lack of controls on N<sub>2</sub>O will undo 25% of the benefit gained by the Montreal Protocol to reducing ODS from the ozone layer.”).

<sup>113</sup> World Meteorological Organization (WMO), United Nations Environment Programme (UNEP), National Oceanic and Atmospheric Administration (NOAA), National Aeronautics and Space Administration (NASA), & European Commission (2018) [\*Executive Summary: Scientific Assessment of Ozone Depletion: 2018\*](#), Global Ozone Research and Monitoring Project-Report No. 58, 1.61. (“As a result of this growth, the contribution of N<sub>2</sub>O to radiative forcing has continued to rise, reaching 0.19 W m<sup>-2</sup> in 2016, approximately 10% that of CO<sub>2</sub>.”).

<sup>114</sup> Harmsen J.H.M., van Vuuren D.P., Nayak D.R., Hof A.F., Höglund-Isaksson L., Lucas P.L., Nielsen J.B., Smith P., & Stehfest E. (2019) [\*Long-term marginal abatement cost curves of non-CO<sub>2</sub> greenhouse gases\*](#), ENV’T SCI. & POL’Y 99:136–149, 145, tbl. 2.



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<sup>115</sup> Environmental Protection Agency (EPA) (2012) [GLOBAL ANTHROPOGENIC NON-CO<sub>2</sub> GREENHOUSE GAS EMISSIONS: 1990–2030](#), at 41 (“Between 1990 and 2005, N<sub>2</sub>O emissions from production of nitric and adipic acid has decreased 37 percent, from 200 MtCO<sub>2</sub>e to 126 MtCO<sub>2</sub>e (see Table 4-2). Over this time period, production of nitric and adipic acid has increased. The decline in historical emissions is mostly due to widespread installation of abatement technologies in the adipic acid industry (Reimer et al, 1999). Most production capacity in these industries has been located in the OECD, but the proportion of emissions in the OECD has declined. In 1990, the OECD accounted for 83 percent of global N<sub>2</sub>O emissions from this source, whereas the OECD is estimated to account for 68 percent of global emissions in 2005.”).

<sup>116</sup> Environmental Protection Agency (EPA) (2019) [GLOBAL NON-CO<sub>2</sub> GREENHOUSE GAS EMISSION PROJECTIONS & MITIGATION: 2015–2050](#), at 29 (“Taken together, the top 5 countries in terms of baseline emissions represent 85% of all potential global abatement in the source category in 2030. China alone represents 67% of total abatement potential, in part because of its high production capacity and lower adoption of emission controls relative to other large producers of nitric and adipic acid.”).

<sup>117</sup> Balafoutis, A., et al. (2017) [Precision Agriculture Technologies Positively Contributing to GHG Emissions Mitigation, Farm Productivity and Economics](#), SUSTAINABILITY 11:1–28, 9 (“Tekin (2010) estimated that VRNA can increase wheat production between 1% and 10% offering savings in nitrogen fertilisation between 4% and 37%.”).

<sup>118</sup> SOP, [SOP. Save Our Planet](#) (last accessed 08 February 2020).

<sup>119</sup> Peterson, C., El Mashad, H. M., Zhao, Y., Pan, Y., & Mitloehner, F. M. (2020) [Effects of SOP Lagoon Additive on Gaseous Emissions from Stored Liquid Dairy Manure](#), SUSTAINABILITY 12:1–17, 14–15 (“These studies seem to indicate that the applied HIGH dose of SOP Lagoon might decrease the number of methanogens that produce methane during the storage of manure as well as hydrolytic microorganisms and their excreted enzymes that biodegrade organic nitrogen into ammonium.”).

<sup>120</sup> Jackson R. B., Solomon, E.I., Canadell, J.G., Cargnello, M., & Field, C.B. (2019) [Methane removal and atmospheric restoration](#), NAT. SUSTAIN. 2:436–438, 436 (“In contrast to negative emissions scenarios for CO<sub>2</sub> that typically assume hundreds of billions of tonnes removed over decades and do not restore the atmosphere to preindustrial levels, methane concentrations could be restored to ~750 ppb by removing ~3.2 of the 5.3 Gt of CH<sub>4</sub> currently in the atmosphere. Rather than capturing and storing the methane, the 3.2 Gt of CH<sub>4</sub> could be oxidized to CO<sub>2</sub>, a thermodynamically favourable reaction.... In total, the reaction would yield 8.2 additional Gt of atmospheric CO<sub>2</sub>, equivalent to a few months of current industrial CO<sub>2</sub> emissions, but it would eliminate approximately one sixth of total radiative forcing. As a result, methane removal or conversion would strongly complement current CO<sub>2</sub> and CH<sub>4</sub> emissions-reduction activities. The reduction in short-term warming, attributable to methane’s high radiative forcing and relatively short lifetime, would also provide more time to adapt to warming from long-lived greenhouse gases such as CO<sub>2</sub> and N<sub>2</sub>O.”). Klaus Lackner critiqued the Jackson *et al.* article in a published response, arguing that implementing zeolite mechanisms to facilitate CH<sub>4</sub> removal is not practical. Lackner noted CH<sub>4</sub> removal faces the challenge of extreme dilution in the atmosphere, so “the amount of air that would need to be moved [to facilitate CH<sub>4</sub> removal] would simply be too great” to be economically feasible. However, Lackner did note passive methods of CH<sub>4</sub> removal through the use of zeolites may still be a viable solution. Lackner further argues that N<sub>2</sub>O may be a more worthy target for removal due to its long lifetime in the atmosphere. See Lackner K. S. (2020) [Practical Constraints on Atmospheric Methane Removal](#), NAT. SUSTAIN. 3:357. Jackson *et al.* published a response to Lackner, acknowledging his stature in the greenhouse gas removal field and his concerns about the feasibility and energy requirements of their proposed mechanism, offering additional explanation about alternative options for use of the captured methane instead of just converting it to CO<sub>2</sub> as suggested in the original study. See Jackson R. B., Solomon E. I., Canadell J. G., Cargnello M., Field C. B., & Abernethy S. (2020) [Reply to: Practical constraints on atmospheric methane removal](#), NAT. SUSTAIN. 3:358–359. Another study looking at removing non-CO<sub>2</sub> GHGs investigated the potential of using solar chimney power plants (SCPPs) with select photocatalysts (depending on what GHGs desired to be captured). While the SCPP serves as a source of renewable energy that could remove methane and nitrous oxide among other atmospheric pollutants, scaling up the prototype would require a massive amount of land area (roughly 23 times the size of the entire Beijing municipality) and a chimney stretching 1000–1500 m into the air, which limits how practical the existing technology may be. See de Richter R., Tingzhen M., Davies P., Wei L., & Caillol S. (2017) [Removal of non-CO<sub>2</sub> greenhouse gases by large-scale atmospheric solar photocatalysis](#), PROG. ENERGY COMBUST. SCI. 60:68–96.

<sup>121</sup> Moomaw W. R., Masino S. A., & Faison E. K. (2019) [Intact Forests in the United States: Proforestation Mitigates Climate Change and Serves the Greatest Good](#), FRONT. FOR. GLOB. CHANGE, Perspective, 2(27):1–10, 1 (“Climate change and loss of biodiversity are widely recognized as the foremost environmental challenges of our time. Forests annually sequester large quantities of atmospheric carbon dioxide (CO<sub>2</sub>), and store carbon above and below ground for long periods of time. Intact forests—largely free from human intervention except primarily for trails and hazard removals—are the most carbon-dense

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and biodiverse terrestrial ecosystems, with additional benefits to society and the economy. ... The recent *1.5 Degree Warming Report* by the Intergovernmental Panel on Climate Change identifies *reforestation* and *afforestation* as important strategies to increase negative emissions, but they face significant challenges: afforestation requires an enormous amount of additional land, and neither strategy can remove sufficient carbon by growing young trees during the critical next decade(s). In contrast, growing existing forests intact to their ecological potential—termed *proforestation*—is a more effective, immediate, and low-cost approach that could be mobilized across suitable forests of all types. Proforestation serves the greatest public good by maximizing co-benefits such as nature-based biological carbon sequestration and unparalleled ecosystem services such as biodiversity enhancement, water and air quality, flood and erosion control, public health benefits, low impact recreation, and scenic beauty.”); and World Wildlife Fund (WWF) (2020) *Living Planet Report 2020 – Bending the curve of biodiversity loss*, Almond R. E. A., Grooten M., & Petersen T. (eds.), 5 (“The global Living Planet Index continues to decline. It shows an average 68% decrease in population sizes of mammals, birds, amphibians, reptiles and fish between 1970 and 2016. ... It matters because biodiversity is fundamental to human life on Earth, and the evidence is unequivocal – it is being destroyed by us at a rate unprecedented in history. Since the industrial revolution, human activities have increasingly destroyed and degraded forests, grasslands, wetlands and other important ecosystems, threatening human well-being. Seventy-five per cent of the Earth’s ice-free land surface has already been significantly altered, most of the oceans are polluted, and more than 85% of the area of wetlands has been lost.”). See also Griscom B. W., et al. (2017) *Natural climate solutions*, PROC. NAT’L. ACAD. SCI. 114(44):11645–11650, 11645 (“Better stewardship of land is needed to achieve the Paris Climate Agreement goal of holding warming to below 2 °C; however, confusion persists about the specific set of land stewardship options available and their mitigation potential. To address this, we identify and quantify “natural climate solutions” (NCS): 20 conservation, restoration, and improved land management actions that increase carbon storage and/or avoid greenhouse gas emissions across global forests, wetlands, grasslands, and agricultural lands. We find that the maximum potential of NCS—when constrained by food security, fiber security, and biodiversity conservation—is 23.8 petagrams of CO<sub>2</sub> equivalent (PgCO<sub>2</sub>e) y<sup>-1</sup> (95% CI 20.3–37.4). This is ≥30% higher than prior estimates, which did not include the full range of options and safeguards considered here. About half of this maximum (11.3 PgCO<sub>2</sub>e y<sup>-1</sup>) represents cost-effective climate mitigation, assuming the social cost of CO<sub>2</sub> pollution is ≥100 USD MgCO<sub>2</sub>e<sup>-1</sup> by 2030. Natural climate solutions can provide 37% of cost-effective CO<sub>2</sub> mitigation needed through 2030 for a >66% chance of holding warming to below 2 °C. One-third of this cost-effective NCS mitigation can be delivered at or below 10 USD MgCO<sub>2</sub>e<sup>-1</sup>. Most NCS actions—if effectively implemented—also offer water filtration, flood buffering, soil health, biodiversity habitat, and enhanced climate resilience. Work remains to better constrain uncertainty of NCS mitigation estimates. Nevertheless, existing knowledge reported here provides a robust basis for immediate global action to improve ecosystem stewardship as a major solution to climate change.”); and P. Raven, et al. (11 February 2021) *Letter Regarding Use of Forests for Bioenergy*, WOODWELL CLIMATE RESEARCH CENTER (“Trees are more valuable alive than dead both for climate and for biodiversity. To meet future net zero emission goals, your governments should work to preserve and restore forests and not to burn them.”).

<sup>122</sup> Lenton T. M., Rockstrom J., Gaffney O., Rahmstorf S., Richardson K., Steffen W., & Schellnhuber H. J. (2019) *Climate tipping points—too risky to bet against*, NATURE, Comment, 575:592–595, 593 (“Estimates of where an Amazon tipping point could lie range from 40% deforestation to just 30% forest-cover loss. About 17% has been lost since 1970. The rate of deforestation varies with changes in policy. Finding the tipping point requires models that include deforestation and climate change as interacting drivers, and that incorporate fire and climate feedbacks as interacting tipping mechanisms across scales.”). See also Lovejoy T. E. & Nobre C. (2018) *Amazon’s Tipping Point*, SCI. ADV. 4:1 (“We believe that negative synergies between deforestation, climate change, and widespread use of fire indicate a tipping point for the Amazon system to flip to nonforest ecosystems in eastern, southern and central Amazonia at 2025% deforestation.”) and Hoegh-Guldberg O., Jacob D., & Taylor M. (2018) *Chapter 3: Impacts of 1.5 °C of Global Warming on Natural and Human Systems*, in *GLOBAL WARMING OF 1.5 °C*, Intergovernmental Panel on Climate Change, 263 (“Global warming of 3°C is projected to reduce the extent of tropical rainforest in Central America, with biomass being reduced by about 40%, which can lead to a large replacement of rainforest by savanna and grassland (Lyra et al., 2017). Overall, modelling studies (Huntingford et al., 2013; Nobre et al., 2016) and observational constraints (Cox et al., 2013) suggest that pronounced rainforest dieback may only be triggered at 3°C–4°C (medium confidence), although pronounced biomass losses may occur at 1.5°C– 2°C of global warming.”).

<sup>123</sup> Lenton T. M., Held H., Kriegler El., Hall J. W., Lucht W., Rahmstorf S., & Schellnhuber H. J. (2008) *Tipping elements in the Earth’s climate system*, PROC. NAT’L. ACAD. SCI. 105(6):1786–1793, 1790 (“A large fraction of precipitation in the Amazon basin is recycled, and, therefore, simulations of Amazon deforestation typically generate 20–30% reductions in precipitation (78), lengthening of the dry season, and increases in summer temperatures (79) that would make it difficult for the forest to reestablish, and suggest the system may exhibit bistability.”). See also Staal A., Fetzer I., Wang-Erlandsson L., Bosmans J. H. C., Dekker S. C., van Nes E. H., Rockström J., & Tuinenburg O. A. (2020), *Hysteresis of tropical forests in the 21<sup>st</sup> century*, NAT. COMMUN. 11(4978):1–8, 5 (“Whether the Amazon in particular is an important global ‘tipping element’ in the Earth system is a question of great scientific and societal interest<sup>36,37</sup>. Despite our incomplete understanding of Amazon

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tipping, it is generally considered to be true that the forest's role in the hydrological cycle is so large that deforestation and/or climate change may trigger a tipping point<sup>2,36–38</sup>. More recently, the possibility of fire-induced tipping has also been suggested<sup>5,6</sup>. Although fire occurs at a local scale, a considerable portion of the Amazon would be susceptible to this kind of tipping; by accounting for the feed-backs at both local and regional scales, it becomes more likely that the Amazon is a tipping element. Although under the current climate a majority of the Amazon forest still appears resilient to disturbance (also see ref. 39), we show that this resilience may deteriorate as a result of redistributions of rainfall due to global climate change.”).

<sup>124</sup> Duffy K. A., Schwalm C. R., Arcus V. L., Koch G. W., Liang L. L., & Schipper L. A. (2021) [How close are we to the temperature tipping point of the terrestrial biosphere?](#), *SCI. ADV.* 7:1–8, 1 (“The temperature dependence of global photosynthesis and respiration determine land carbon sink strength. While the land sink currently mitigates ~30% of anthropogenic carbon emissions, it is unclear whether this ecosystem service will persist and, more specifically, what hard temperature limits, if any, regulate carbon uptake. Here, we use the largest continuous carbon flux monitoring network to construct the first observationally derived temperature response curves for global land carbon uptake. We show that the mean temperature of the warmest quarter (3-month period) passed the thermal maximum for photosynthesis during the past decade. At higher temperatures, respiration rates continue to rise in contrast to sharply declining rates of photosynthesis. Under business-as-usual emissions, this divergence elicits a near halving of the land sink strength by as early as 2040.”). See also Hubau W., et al. (2020) [Asynchronous carbon sink saturation in African and Amazonian tropical forests](#), *NATURE* 579:80–87, 85 (“In summary, our results indicate that although intact tropical forests remain major stores of carbon and are key centres of biodiversity<sup>11</sup>, their ability to sequester additional carbon in trees is waning. In the 1990s intact tropical forests removed 17% of anthropogenic CO<sub>2</sub> emissions. This declined to an estimated 6% in the 2010s, because the pan-tropical weighted average per unit area sink strength declined by 33%, forest area decreased by 19% and anthropogenic CO<sub>2</sub> emissions increased by 46%. Although tropical forests are more immediately threatened by deforestation<sup>46</sup> and degradation<sup>47</sup>, and the future carbon balance will also depend on secondary forest dynamics<sup>48</sup> and forest restoration plans<sup>49</sup>, our analyses show that they are also affected by atmospheric chemistry and climatic changes. Given that the intact tropical forest carbon sink is set to end sooner than even the most pessimistic climate driven vegetation models predict<sup>4,5</sup>, our analyses suggest that climate change impacts in the tropics may become more severe than predicted. Furthermore, the carbon balance of intact tropical forests will only stabilize once CO<sub>2</sub> concentrations and the climate stabilizes.”).

<sup>125</sup> Duffy K. A., Schwalm C. R., Arcus V. L., Koch G. W., Liang L. L., & Schipper L. A. (2021) [How close are we to the temperature tipping point of the terrestrial biosphere?](#), *SCI. ADV.* 7:1–8, 3 (“This...calls into question the future viability of the land sink, along with Intended Nationally Determined Contributions (INDCs) within the Paris Climate Accord, as these rely heavily on land uptake of carbon to meet pledges. In contrast to Representative Concentration Pathway 8.5 (RCP8.5), warming associated with scenario RCP2.6 could allow for near-current levels of biosphere productivity, preserving the majority land carbon uptake (~10 to 30% loss).”).

<sup>126</sup> Moomaw W.R., Masino S.A., & Faison E.K. (2019) [Intact Forests in the United States: Proforestation Mitigates Climate Change and Serves the Greatest Good](#), *FRONT. FOR. GLOB. CHANGE* 2(27):1–10, 1 (“The recent 1.5 Degree Warming Report by the Intergovernmental Panel on Climate Change identifies *reforestation* and *afforestation* as important strategies to increase negative emissions, but they face significant challenges: afforestation requires an enormous amount of additional land, and neither strategy can remove sufficient carbon by growing young trees during the critical next decade(s). In contrast, growing existing forests intact to their ecological potential—termed *proforestation*—is a more effective, immediate, and low-cost approach that could be mobilized across suitable forests of all types. Proforestation serves the greatest public good by maximizing co-benefits such as nature-based biological carbon sequestration and unparalleled ecosystem services such as biodiversity enhancement, water and air quality, flood and erosion control, public health benefits, low impact recreation, and scenic beauty.”).

<sup>127</sup> Crump J. (ed.) (2017) [Smoke on Water: Countering Global Threats from Peatlands Loss and Degradation](#), *UNEP Rapid Response Assessment*, United Nations Environment Programme and GRID-Arendal, 9 (“Current greenhouse gas emissions from drained or burning peatlands are estimated to be up to five percent of all emissions caused by human activity – in the range of two billion tonnes of CO<sub>2</sub> per year. If the world has any hope of keeping the global average temperature increase under two degrees Celsius then urgent action must be taken to keep the carbon locked in peatlands where it is – wet, and in the ground to prevent an increase in emissions. Furthermore, already drained peatlands must be rewetted to halt their ongoing significant emissions. However, this is not as simple as it seems. Knowing the location of peatlands continues to be a challenge.”); F. Humpeöder, K. Karstens, H. Lotze-Campen, J. Leifeld, L. Menichetti, A. Barthelmes, & A. Popp (2020) [Peatland Protection and Restoration are Key for Climate Change Mitigation](#), *ENV'T RSCH. LETT.* 15(10):1–12, 10 (“However, in line with other studies (Leifeld et al 2019), our results indicate that it is possible to reconcile land use and GHG emissions in mitigation pathways through a peatland protection and restoration policy (RCP2.6 + PeatRestor). Our results suggest that the land system would turn into a global net carbon sink by 2100, as projected by current mitigation

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pathways, if about 60% of present-day degraded peatlands, mainly in the tropical and boreal climate zone, would be rewetted in the coming decades, next to the protection of intact peatlands. Therefore, peatland protection and restoration are key for climate change mitigation. At the same time, our results indicate that the implementation costs of peatland protection and restoration measures are low, and that there are almost no impacts on regional food security.”).

<sup>128</sup> Intergovernmental Panel on Climate Change (IPCC) (2019) *Summary for Policymakers*, in [IPCC SPECIAL REPORT ON THE OCEAN AND CRYOSPHERE IN A CHANGING CLIMATE](#), Pörtner H.-O., *et al.* (eds.), 30 (“Restoration of vegetated coastal ecosystems, such as mangroves, tidal marshes and seagrass meadows (coastal ‘blue carbon’ ecosystems), could provide climate change mitigation through increased carbon uptake and storage of around 0.5% of current global emissions annually (medium confidence). Improved protection and management can reduce carbon emissions from these ecosystems.”).

<sup>129</sup> Intergovernmental Panel on Climate Change (IPCC) *Summary for Policymakers*, in [GLOBAL WARMING OF 1.5 °C](#), Masson-Delmotte, V. P., *et al.* (eds.), 6 (“Human activities are estimated to have caused approximately 1.0 °C of global warming above pre-industrial levels, with a *likely* range of 0.8 °C to 1.2 °C. Global warming is *likely* to reach 1.5 °C between 2030 and 2052 if it continues to increase at the current rate. (*high confidence*).”). In addition to cutting CO<sub>2</sub> emissions and emissions of the super climate pollutants, the IPCC 1.5 °C Report also calculates the need for significant CO<sub>2</sub> removal. *Id.*, at 17 (“C.3. All pathways that limit global warming to 1.5°C with limited or no overshoot project the use of carbon dioxide removal (CDR) on the order of 100–1000 GtCO<sub>2</sub> over the 21st century.”).

<sup>130</sup> Xu Y. & Ramanathan V. (2017) [Well below 2 °C: Mitigation strategies for avoiding dangerous to catastrophic climate changes](#), PROC. NAT’L. ACAD. SCI. 114(39):10315–10323, 10319 (“Box 2. Risk Categorization of Climate Change to Society. ... Warming of such magnitudes also has catastrophic human health effects. Many recent studies (**50**, **51**) have focused on the direct influence of extreme events such as heat waves on public health by evaluating exposure to heat stress and hyperthermia. It has been estimated that the likelihood of extreme events (defined as 3-sigma events), including heat waves, has increased 10-fold in the recent decades(**52**). Human beings are extremely sensitive to heat stress. For example, the 2013 European heat wave led to about 70,000 premature mortalities (**53**). The major finding of a recent study (**51**) is that, currently, about 13.6% of land area with a population of 30.6% is exposed to deadly heat. ... According to this study, a 2 °C warming would double the land area subject to deadly heat and expose 48% of the population. A 4 °C warming by 2100 would subject 47% of the land area and almost 74% of the world population to deadly heat, which could pose existential risks to humans and mammals alike unless massive adaptation measures are implemented, such as providing air conditioning to the entire population or a massive relocation of most of the population to safer climates. ... This bottom 3 billion population comprises mostly subsistent farmers, whose livelihood will be severely impacted, if not destroyed, with a one- to five-year megadrought, heat waves, or heavy floods; for those among the bottom 3 billion of the world’s population who are living in coastal areas, a 1- to 2-m rise in sea level (likely with a warming in excess of 3°C) poses existential threat if they do not relocate or migrate. It has been estimated that several hundred million people would be subject to famine with warming in excess of 4 °C (**54**). However, there has essentially been no discussion on warming beyond 5 °C. Climate change-induced species extinction is one major concern with warming of such large magnitudes (>5°C). The current rate of loss of species is ~1,000-fold the historical rate, due largely to habitat destruction. At this rate, about 25% of species are in danger of extinction in the coming decades (**56**). Global warming of 6°C or more (accompanied by increase in ocean acidity due to increased CO<sub>2</sub>) can act as a major force multiplier and expose as much as 90% of species to the dangers of extinction (**57**). The bodily harms combined with climate change-forced species destruction, biodiversity loss, and threats to water and food security, as summarized recently (**58**), motivated us to categorize warming beyond 5°C as unknown??, implying the possibility of existential threats.”).

<sup>131</sup> Steffen W., *et al.* (2018) [Trajectories of the Earth System in the Anthropocene](#), PROC. NAT’L. ACAD. SCI. 115(33):8252–8259, 8254, 8256 (“This risk is represented in [Figs. 1](#) and [2](#) by a planetary threshold (horizontal broken line in [Fig. 1](#) on the Hothouse Earth pathway around 2 °C above preindustrial temperature). Beyond this threshold, intrinsic biogeophysical feedbacks in the Earth System (*Biogeophysical Feedbacks*) could become the dominant processes controlling the system’s trajectory. Precisely where a potential planetary threshold might be is uncertain ([15](#), [16](#)). We suggest 2 °C because of the risk that a 2 °C warming could activate important tipping elements ([12](#), [17](#)), raising the temperature further to activate other tipping elements in a domino-like cascade that could take the Earth System to even higher temperatures (*Tipping Cascades*). Such cascades comprise, in essence, the dynamical process that leads to thresholds in complex systems (section 4.2 in ref. [18](#)). This analysis implies that, even if the Paris Accord target of a 1.5 °C to 2.0 °C rise in temperature is met, we cannot exclude the risk that a cascade of feedbacks could push the Earth System irreversibly onto a “Hothouse Earth” pathway. ... Hothouse Earth is likely to be uncontrollable and dangerous to many, particularly if we transition into it in only a century or two, and it poses severe risks for health, economies, political stability ([12](#), [39](#), [49](#), [50](#)) (especially for the most climate vulnerable), and ultimately, the habitability of the planet for humans.”).