3 June 2022
Secretariat of the Human Rights Council Advisory Committee
Human Rights Council Branch
Human Rights Council and Treaty Mechanisms Division
Office of the United Nations High Commissioner for Human Rights
United Nations Office at Geneva
CH-1211 Geneva 10, Switzerland

RE: CHRE & IGSD Comments on NTCPs

To the Office of the High Commissioner for Human Rights,

We are grateful to the Office of the High Commissioner for Human Rights and the Special Rapporteur on the Promotion and Protection of Human Rights in the Context of Climate Change for the opportunity to submit our recommendations on the impact of new technologies for climate protection on the advancement of human rights. We submit this comment on behalf of the Center for Human Rights & Environment (CHRE) and the Institute for Governance & Sustainable Development (IGSD).[*] The climate crisis is an unprecedented, escalating human rights emergency that hits disadvantaged climate-vulnerable communities the hardest, with particularly significant impacts on women and children. New technologies for climate protection will be critical to avoid its worst impacts, but they may, in themselves, pose new threats to human rights.

Climate change poses the greatest threat to human rights. Limiting warming to 1.5°C (above pre-industrial levels) with little or no overshoot in both the near and longer term is necessary to limit risks to vulnerable and threatened human and natural systems as well as the added pressures associated with climate feedbacks and crossing irreversible tipping points.[1] Beyond the 1.5°C guardrail, these risks increase, including the risk of triggering a cascade of tipping points committing human and natural systems to potentially abrupt and irreversible changes. The magnitude and rate of these changes may exceed the capacity of systems to adapt.[2]

Over 3 billion people currently live in areas that are highly vulnerable to climate change.[3] Many communities are already experiencing the early impacts of a rapidly warming world, such as heatwaves, droughts, and other extreme weather events that exacerbate already-existing health risks.[4] These frontline communities, primarily in developing countries and in historically marginalized communities, have contributed the least to climate change but are bearing the worst of its impacts.[5]

Strengthening the resilience of communities requires reducing risk through fast action mitigation, adaptation, and societal transformation. Therefore, a fast climate mitigation strategy is the best way to address the immediate needs of the most marginalized communities.

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[*] With special acknowledgements to Amelia Murphy (CHRE/IGSD), Caitlan Frederick (IGSD), Erika Gerstenberger (IGSD), Gabrielle Dreyfus (IGSD), Jon Turner (IGSD), Jorge Daniel Taillant (CHRE/IGSD), Sophie Crawford (CHRE), and Trina Thorbjornsen (IGSD) for their work on reviewing and compiling these comments.

The Intergovernmental Panel on Climate Change further confirms the need for fast action in their Working Group II contribution to their Sixth Assessment Report:[6]

> "Global warming, reaching 1.5°C in the near-term, would cause unavoidable increases in multiple climate hazards and present multiple risks to ecosystems and humans (*very high confidence*). The level of risk will depend on concurrent near-term trends in vulnerability, exposure, level of socioeconomic development and adaptation (*high confidence*). Near-term actions that limit global warming to close to 1.5°C would substantially reduce projected losses and damages related to climate change in human systems and ecosystems, compared to higher warming levels, but cannot eliminate them all (*very high confidence*)."

Climate mitigation efforts have mostly focused on reducing emissions of carbon dioxide (CO_2). Anthropogenic sources of CO_2 largely come from the combustion of fossil fuels, so efforts to decarbonize have been the primary focus to avoid further warming. But CO_2 is not the only pollutant warming the planet, and decarbonization strategies alone cannot keep us from passing the 1.5°C guardrail.[7]

The best short-term strategy to complement a longer-term CO_2 reduction strategy and avoid the most warming by 2030 is to reduce short-lived climate pollutants (SLCPs, or super pollutants) as quickly as possible. SLCPs include methane (CH_4), tropospheric ozone (O_3, or smog), black carbon (soot), and hydrofluorocarbon (HFCs, often used as refrigerants). These super climate pollutants must be cut as quickly as possible, along with other fast mitigation strategies, including the protection of currently existing sinks, like forests, peatlands, and soils, that naturally contain and take out CO_2 from the atmosphere. Focusing on SLCPs is an important short-term strategy because of their high global warming potentials (GWP) and short atmospheric life, and if cut quickly, can quickly reduce warming.

These strategies are complementary and not exchangeable. A dual strategy that simultaneously reduces CO_2 and SLCP emissions (particularly methane) and protect sinks would enable the world to stay below the 1.5°C guardrail and can provide immediate local and global health benefits, particularly to disadvantaged communities. Of these three strategies, cutting SLCPs can slow warming one to two decades sooner than CO_2-focused strategies alone, avoid two to six times more warming at 2050 than CO_2 cuts can,[8] and reduce projected warming in the Arctic by two-thirds and the rate of global warming by half.[9]

In addition to the answers to the core questions (see pages 4–8), we are submitting two papers written by IGSD for additional information on the technologies we want to raise awareness on. The first paper, 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*, reviews the science of the need for fast mitigation and the role of SLCPs in quickly reducing warming. The second paper, A CALL TO STOP BURNING TREES IN THE NAME OF CLIMATE MITIGATION, discusses the threat of bioenergy with carbon capture storage (BECCS), which is not a carbon neutral climate strategy and will accelerate warming for decades. BECCS also poses immediate risks to human rights due to increased air pollution, rising competition for land, water, and other essential resources, risks to biodiversity, and for its contribution to warming.

We recommend SLCP reduction technologies for their capacity to deliver immediate cooling benefits, slow global warming, and avoid irreversible climate tipping points. These technologies directly benefit the human right to health, as well as reducing the harm inflicted by current and future climate-related crises that will ultimately interfere with additional human rights, particularly the rights to life and a sustainable environment. We also want to emphasize that the second technology highlighted in the second article, BECCS, actually **threatens** human rights and should **not** be considered a climate justice solution.

Fast action to combat climate change is essential to reduce impacts on communities and ensure the right to a clean, healthy, and sustainable environment and right to life for present and future generations. We recommend that human rights and climate stakeholders advocate for increased investment in strategies that will maximize near-term warming reductions, such as those that reduce methane and those that provide equitable cooling, as well as foster more communication among and between various government agencies, communities, and stakeholder groups. The climate affects us all, and we must act now to ensure protection of human rights in the face of planetary despair.

Sincerely,

CHRE Center for Human Rights & Environment

and

IGSD Institute for Governance & Sustainable Development

1. Which New Technologies for Climate Protection (NTCPs) are of particular importance when it comes to impact on human rights?

CHRE and IGSD recommend fast action mitigation strategies for their capacity to deliver immediate cooling benefits, slow global warming, and avoid irreversible tipping points. These technologies directly benefit the human right to health, as well as reducing the harm inflicted by current and future climate-related crises that will ultimately interfere with additional human rights, particularly the rights to life and a healthy environment. These strategies include technologies that reduce emissions of short-lived climate pollutants (SLCPs, or "super pollutants"), protecting forests and other sinks, and methane and CO_2 removal strategies, including solar radiation management and restoring Arctic ice albedo. For detailed information on these technologies, *see* IGSD & CHRE (2022) 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.

In addition, bioenergy with carbon capture & storage (BECCS) is being proposed as an NTCP but it does not protect human rights and in fact, threatens the environment and nearby communities. BECCS is not carbon neutral in the near-term, with a carbon deficit for many years—generally several decades to a century. For detailed information on its adverse human rights and environmental impact, *see* Bloomer L., Sun X., Dreyfus G., Ferris T., Zaelke D., & Schiff C. (2021) *A Call to Stop Burning Trees in the Name of Climate Mitigation*, VERMONT JOURNAL OF ENVIRONMENTAL LAW 23.

2. What kind of NTCP may contribute to human rights promotion and protection?

The key message we'd like to convey in our comments is that fast mitigation of SLCPs, as well as avoided warming strategies (such as increasing albedo) can have immediate climate benefits that instantly improve lives and subsequently contribute to human rights protection, including the right to health, property, development, work, water, and more. Strengthening the resilience of communities requires reducing risk through fast action mitigation, in addition to adaptation and societal transformation.

We must also stress that the contextual urgency we face to avoid breaching irreversible and potentially catastrophic climate tipping points has profound implications for the ability of future generations to realize human rights. We refer to this as the Climate Equity Paradox,[10] which can be summed up as the sobering reality that all current efforts to slow, stop, or reverse global warming and/or to avoid or to alleviate the impacts of climate change (or the avoidance of the human rights impacts that it causes), may be in fact useless if climate tipping points are breached. Surpassing irreversible and catastrophic climate tipping points in the near term would essentially bar future generations from enjoying human rights that are, and will be, threatened by global warming.

The super pollutant reduction strategy, as described in 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*, can most effectively and rapidly tackle climate warming while providing immediate alleviation of climate impacts to the most climate-vulnerable communities, especially in the Arctic.

3. **What are the key human rights challenges and risks arising from NTCP and from which in particular? Do NTCP create unique and unprecedented challenges or risks, or are there earlier precedents that help us understand the issue area?**

Bioenergy with carbon capture & storage (BECCS) is being proposed as an NTCP but it does not protect human rights and in fact, threatens the environment and nearby communities. BECCS is not carbon neutral in the near-term, with a carbon deficit for many years—generally several decades to a century. For detailed information on its adverse human rights and environmental impact, *see* Bloomer L., Sun X., Dreyfus G., Ferris T., Zaelke D., & Schiff C. (2021) *A Call to Stop Burning Trees in the Name of Climate Mitigation*, VERMONT JOURNAL OF ENVIRONMENTAL LAW 23.

4. **What specific human rights may be affected by the use of NTCP? Please, explain how. Who are the rights-holders that potentially would be the most affected by the use of NTCP? Are they also the most affected by climate change? How could they and the society at large be engaged in the decision-making process?**

The use of NTCPs has considerable potential to enhance quality of life for global populations and avoid threats to the human rights of those most vulnerable. The rights-holders who will be most severely impacted by climate change are also those who will benefit most greatly and immediately from the use of NTCP, including in coastal communities, low-income communities, and minority communities. For example, use of Arctic-relevant SRM can slow or stop loss of Arctic ice sheets, which provides protection to the homes, subsistence, financial livelihoods, and personal safety of those in the Arctic, including Indigenous Arctic populations. Moreover, these technologies provide global benefits to sensitive communities—the same Arctic-relevant SRM practices that safeguard Arctic communities will protect those in vulnerable coastal communities across the globe who are at risk from rising sea levels.

There may be some direct or indirect risks and adverse impacts associated with attempts to address climate change through technologies that intervene in the climate. These result from direct chemical, temperature, or other influences that alter climate conditions which in turn could have impacts for rights-holders that reside in the affected areas.

While this section considers the tangible impacts of emerging technologies to slow climate change, we must also consider the eventual magnitude and the full implications of *not* intervening with these technologies to slow and reverse climate change trends before irreparable and catastrophic tipping points are reached. For certain populations, climate change could mean an annihilation of an entire region or country, such as low-lying island states that may be completely submerged due to sea level rise. It is unrealistic to weigh an impact of lower productivity on crop yield when an entire farm region may end up at the bottom of the sea.

The reality is that the added, or marginal, effects of deploying SRM strategies at a global scale remains poorly understood,[11] which is further complicated by the general uncertainty over how severe expected climate impacts may play out on the assurance of the protection of affected human rights for climate-vulnerable communities.[12]

Another key dimension of climate policy has to do with where it is employed. Identifying climate-vulnerable communities, especially minority, low-income, or historically excluded communities, can shed light on where employing aggressive climate technologies could lead to a reversal of historical and systemic discrimination that has led to these inequities in the first place. One strategy is to implement smart surfaces in low-income urban areas to immediately remedy extreme local warming, where residents experience temperatures that are several degrees hotter than neighboring suburban communities that are much cooler due to having better infrastructure and more green spaces.[13] The human rights impacted by extreme climate conditions in already vulnerable communities can be successfully addressed by the use of key NTCPs that both aggressively tackle global warming but also pointedly address inequities.

All decisions about the identification, deployment, and implementation of technologies that will effectively tackle climate change should be vetted through an environmental justice, climate equity and human rights lens, identifying and maximizing opportunities to protect the human rights of the most climate-vulnerable communities.

5. **Is the existing international and your national human rights framework adequate to safeguarding human rights of those affected by the use of NTCP? Why or why not? If not, what principles may be identified in order to address the gaps? List them according to priority.**

Issues of disproportionality—to whom human rights laws are applied and whom they are created to protect—must be addressed as we move toward human-rights approaches to NTCP.[14] Existing human rights frameworks may need to be reworked to consider issues of accessibility and fairness. Current climate policies will result in surpassing irreversible climate tipping points in the near term, making the realization of many human rights unattainable for future generations. Current climate policy and global mitigation commitments are insufficient to provide the human right to a clean, healthy, and sustainable environment for future generations. Continued failure to act will rob humanity of the right to life if we reach the "Hothouse Earth" scenario.[15] Therefore, we must deploy the best available technologies to slow warming both in the near- and long-term to avoid the worst of climate impacts. The current failure to deploy the best available technology to both slow warming and avoid impacts to vulnerable communities result in a Climate Equity Paradox where, despite deep and growing efforts to tackle climate change through decarbonization strategies, we are actually deepening its long-term and irreversible impacts.[16]

In considering the urgency of the climate emergency along with policies that immediately mitigate SLCPs, intergenerational justice and climate equity should be key guiding principles in the formulation of climate policy at a national and local level, particularly where climate-vulnerable communities are also identified as low-income or otherwise socially and economically disadvantaged. Failure to consider time as a function of the success of climate policy will equally impact present and future generations' ability to enjoy the right to a clean, healthy environment. A dual strategy helps ensure that we do not surpass irreversible tipping points and avoid certain climate collapse for future generations.

It is also critical to provide avenues for affected people to turn to when the right to a healthy environment is threatened. Policy and legal frameworks will have to be adaptable to provide mechanisms by which the most affected people and areas can seek redress, including through litigation. For example, California's Assembly Bill 617 provides the opportunity for the most impacted and overburdened communities to receive state funding to implement sustainable, community-based emissions reduction programs. Such policies will continue to be important as more areas become affected by various climate tipping points.

6. Given that NTCP may present potential risks for the enjoyment of human rights, to what extent do human rights legal obligations require the States to pursue other climate protection policies presenting less risks of harm, including mitigation and adaptation measures?

Climate change poses an existential threat to humanity, particularly in historically marginalized communities, so this question requires striking a balance between the minimization of rights impacts to current generations while ensuring we do not surpass irreversible climate tipping points. Protecting the climate and human rights must incorporate the need for speed, as failure to curb warming in the near-term poses a threat to human survival. States have an obligation to weigh the risks of harm from each potential course of action, keeping in mind that "everyone has the right to life, liberty and security of person."[17] The technologies we have proposed are low-cost, can be deployed today, and interfere minimally if at all.

Careful consideration should be given to the mix of mitigation and adaptation technologies deployed, particularly those technologies not adequately vetted for maximizing human rights benefits or decisions that miss the opportunity to do both most effectively. Further considerations would be necessary to weigh the pros and cons of policies that solely target climate adaptation but with no climate mitigation benefit, such as choosing between policies that improve air quality and have climate benefits (e.g., climate-friendly air conditioning systems) as opposed to policies or technologies that only have climate adaptation benefits (e.g., raising homes prone to climate-induced flooding).

7. As opposed to focusing on a selected few technologies, do you think a holistic and inclusive approach will help reduce any gaps in the existing system for addressing human rights challenges from NTCP?

Holistic approaches on climate mitigation and adaptation are recommended for anything that considers climate change impacts and human livelihoods, two topics influenced by a multitude of cultural, environmental, and social variables. Focusing narrowly on ultra-specific mitigation measures may result in adverse climate and human health impacts—for example, lithium extraction for renewable energy ventures is destroying local ecosystems and impacting the sustainability of communities in Chile.[18]

Additionally, the climate system is complex and not easily understood, so human intervention strategies must consider the context of the entire climate system and its inhabitants. Adjustments to the climate and its interrelated planetary effects need to account for the lived realities of those that will be directly and indirectly impacted. A holistic approach, considering who “wins” and who “loses” from any climate mitigation and adaptation strategy is essential to determine whether a strategy is worth pursuing, or whether we are sacrificing human rights over climate impact concerns.

8. What should be the responsibilities of key stakeholders (UN agencies, states, NHRIs, civil society, technical community and academia, private sector) in mitigating the risks of NTCP to human rights and/or fostering its protection?

All key climate and human rights stakeholders must recognize the required urgency of climate action to keep us from breaching 1.5°C before irreversible climate changes occur. We must consider mitigating actions in both the short- and long-term: short-term targets are essential for delaying and ultimately avoiding irreversible tipping points by reduction of SLCPs, and long-term targets (i.e., decarbonization) are essential for stabilizing the climate system and increasing resilience against climate change. All strategies must be clear on the temporal dimensions of actions and attempt to maximize benefits to address the impacts to most climate vulnerable communities as a priority, where possible.

Key stakeholders must bear in mind the short timeline we are working with when analyzing how much further research and development we can afford to invest before acting—if we do not solve the immediate emergency, we will face irreversible planetary changes that threaten the human rights of every person on this planet.

References

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[1] Lenton T. M., Rockstrom J., Gaffney O., Rahmstorf S., Richardson K., Steffen W., & Schellnhuber H. J. (2019) *Climate tipping points—too risky to bet against*, Comment, Nature 575(7784): 592–595, 592 ("Models suggest that the Greenland ice sheet could be doomed at 1.5 °C of warming3, which could happen as soon as 2030. …The world's remaining emissions budget for a 50:50 chance of staying within 1.5 °C of warming is only about 500 gigatonnes (Gt) of CO_2. Permafrost emissions could take an estimated 20% (100 Gt CO_2) 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_2 and boreal forests a further 110 Gt CO_2. With global total CO_2 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."). *See also* Ripple W. J., Wolf C., Newsome T. M., Gregg J. W., Lenton T. M., Palomo I., Eikelboom J. A. J., Law B. E., Huq S., Duffy P. B., & Rockström J. (2021) *World Scientists' Warning of a Climate Emergency 2021*, BioScience: biab079, 1–5, 1 ("There is also mounting evidence that we are nearing or have already crossed tipping points associated with critical parts of the Earth system, including the West Antarctic and Greenland ice sheets, warm-water coral reefs, and the Amazon rainforest.").

[2] Intergovernmental Panel on Climate Change (2022) *Summary for Policymakers*, *in* Climate Change 2022: Impacts, Adaptation, and Vulnerability, *Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Pörtner H.-O., *et al.* (eds.), SPM-11, SPM-13 ("Approximately 3.3 to 3.6 billion people live in contexts that are highly vulnerable to climate change (*high confidence*)."; "Levels of risk for all Reasons for Concern (RFC) are assessed to become high to very high at lower global warming levels than in AR5 (*high confidence*). Between 1.2°C and 4.5°C global warming level very high risks emerge in all five RFCs compared to just two RFCs in AR5 (*high confidence*). Two of these transitions from high to very high risk are associated with near-term warming: risks to unique and threatened systems at a median value of 1.5°C [1.2 to 2.0] °C (*high confidence*) and risks associated with extreme weather events at a median value of 2°C [1.8 to 2.5] °C (*medium confidence*). Some key risks contributing to the RFCs are projected to lead to widespread, pervasive, and potentially irreversible impacts at global warming levels of 1.5–2°C if exposure and vulnerability are high and adaptation is low (*medium confidence*)."; "**SPM.B.3** Global warming, reaching 1.5°C in the near-term, would cause unavoidable increases in multiple climate hazards and present multiple risks to ecosystems and humans (*very high confidence*). The level of risk will depend on concurrent near-term trends in vulnerability, exposure, level of socioeconomic development and adaptation (*high confidence*).").

[3] Intergovernmental Panel on Climate Change (2022) *Summary for Policymakers*, *in* Climate Change 2022: Impacts, Adaptation, and Vulnerability, *Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Pörtner H.-O., *et al.* (eds.), SPM-14 ("Approximately 3.3 to 3.6 billion people live in contexts that are highly vulnerable to climate change (high confidence). A high proportion of species is vulnerable to climate change (high confidence). Human and ecosystem vulnerability are interdependent (high confidence). Current unsustainable development patterns are increasing exposure of ecosystems and people to climate hazards (high confidence).").

[4] Romanello M., *et al.* (2021) *The 2021 report of the Lancet Countdown on health and climate change: code red for a healthy future*, The Lancet 398(10311): 1619–1662, 1619–1620 ("The 44 indicators of this report expose an unabated rise in the health impacts of climate change and the current health consequences of the delayed and inconsistent response of countries around the globe—providing a clear imperative for accelerated action that puts the health of people and planet above all else…. Through these effects, rising average temperatures, and altered rainfall patterns, climate change is beginning to reverse years of progress in tackling the food and water insecurity that still affects the most underserved populations around the world, denying them an essential aspect of good health.").

[5] *See generally* Islam N. & Winkel J. (2017) *Climate Change and Social Inequality*, United Nations Department of Economic and Social Affairs Working Paper No. 152.

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[6] Intergovernmental Panel on Climate Change (2022) *Summary for Policymakers*, *in* CLIMATE CHANGE 2022: IMPACTS, ADAPTATION, AND VULNERABILITY, *Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Pörtner H.-O., *et al.* (eds.), SPM-13 ("**SPM.B.3** Global warming, reaching 1.5°C in the near-term, would cause unavoidable increases in multiple climate hazards and present multiple risks to ecosystems and humans (*very high confidence*). The level of risk will depend on concurrent near-term trends in vulnerability, exposure, level of socioeconomic development and adaptation (*high confidence*). Near-term actions that limit global warming to close to 1.5°C would substantially reduce projected losses and damages related to climate change in human systems and ecosystems, compared to higher warming levels, but cannot eliminate them all (*very high confidence*).").

[7] Intergovernmental Panel on Climate Change (2022) *Summary for Policymakers*, *in* CLIMATE CHANGE 2022: MITIGATION OF CLIMATE CHANGE, *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Shukla P. R., *et al.* (eds.), SPM-31 ("In modelled global low emission pathways, the projected reduction of cooling and warming aerosol emissions over time leads to net warming in the near- to mid-term. In these mitigation pathways, the projected reductions of cooling aerosols are mostly due to reduced fossil fuel combustion that was not equipped with effective air pollution controls."). *See also* Naik V., *et al.* (2021) *Chapter 6: Short-lived climate forcers*, in CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 6-8 ("Additional CH_4 and BC mitigation would contribute to offsetting the additional warming associated with SO_2 reductions that would accompany decarbonization (*high confidence*)."); Ramanathan V. & Feng Y. (2008) *On avoiding dangerous anthropogenic interference with the climate system: Formidable challenges ahead*, PROC. NAT'L. ACAD. SCI. 105(38): 14245–14250, 14248 ("Switching from coal to ''cleaner'' natural gas will reduce CO_2 emission and thus would be effective in minimizing future increases in the committed warming. However, because it also reduces air pollution and thus the ABC [Atmospheric Brown Cloud] masking effect, it may speed up the approach to the committed warming of 2.4°C (1.4–4.3°C)."); *and* United Nations Environment Programme & World Meteorological Organization (2011) INTEGRATED ASSESSMENT OF BLACK CARBON AND TROPOSPHERIC OZONE, 254 ("Evaluating global mean temperature change, it was found that the targeted measures to reduce emissions of methane and BC could greatly reduce warming rates over the next few decades (Figure 6.1; Box 6.1). When all measures are fully implemented, warming during the 2030s relative to the present would be only half as much as in the reference scenario. In contrast, even a fairly aggressive strategy to reduce CO_2 emissions, as for the CO_2-measures scenario, does little to mitigate warming until after the next 20-30 years (Box 6.2). In fact, sulphur dioxide (SO_2) is coemitted with CO_2 in some of the most highly emitting activities, coal burning in large-scale combustion such as in power plants, for example, that are obvious targets for reduced usage under a CO_2-emissions mitigation strategy. Hence such strategies can lead to additional near-term warming (Figure 6.1), in a well-known temporary effect (e.g. Raes and Seinfeld, 2009), although most of the nearterm warming is driven by CO_2 emissions in the past. The CO_2-measures scenario clearly leads to long-term benefits however, with a dramatically lower warming rate at 2070 under that scenario than under the scenario with only CH_4 and BC measures (see Figure 6.1 and timescales in Box 6.2). Hence the near-term measures clearly cannot be substituted for measures to reduce emissions of long-lived GHGs. The near-term measures largely target different source sectors for emissions than the CO_2 measures, so that the emissions reductions of the short-lived pollutants are almost identical regardless of whether the CO_2 measures are implemented or not, as shown in Chapter 5. The near-term measures and the CO_2 measures also impact climate change over different timescales owing to the different lifetimes of these substances. In essence, the near-term CH_4 and BC measures are effectively uncoupled from CO_2 measures examined here.").

[8] Dreyfus G. B., Xu Y., Shindell D. T., Zaelke D., & Ramanathan V. (2022) *Mitigation climate disruption in time: A self-consistent approach for avoiding both near-term and long-term global warming*, PROC. NAT'L. ACAD. SCI. 119(22): e2123536119 ("We find that mitigation measures that target only decarbonization are essential for strong long-term cooling but can result in weak near-term warming (due to unmasking the cooling effect of co-emitted aerosols) and lead to temperatures exceeding 2°C before 2050. In contrast, pairing decarbonization with additional mitigation measures targeting short-lived climate pollutants (SLCPs) and N_2O, slows the rate of warming a decade or two earlier than decarbonization alone and avoids the 2°C threshold altogether. These non-CO_2 targeted measures when combined with decarbonization can provide net cooling by 2030, reduce the rate of warming from 2030 to 2050 by about 50%, roughly half of which comes from methane, significantly larger than decarbonization alone over this timeframe."). *See also* Xu Y. & Ramanathan V. (2017) *Well below 2 °C: Mitigation strategies for avoiding dangerous to catastrophic climate changes*, PROC. NAT'L. ACAD. SCI. 114(39): 10315–10323, 10321 ("Constrained by CO_2 lifetime and the diffusion time of new technologies (decades), the scenarios considered here (SI Appendix, Fig. S2A)

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suggest that about half of the 2.6 °C CO_2 warming in the baseline-fast scenario can be mitigated by 2100 and only 0.1–0.3 °C can be mitigated by 2050… The SP [super pollutant] lever targets SLCPs. Reducing SLCP emissions thins the SP blanket within few decades, given the shorter lifetimes of SLCPs (weeks for BC to about 15 years for HFCs). The mitigation potential of the SP lever with a maximum deployment of current technologies … is about 0.6 °C by 2050 and 1.2 °C by 2100 (SI Appendix, Fig. S5B and Table S1)."); *and* Naik V., *et al.* (2021) *Chapter 6: Short-lived climate forcers*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 6-6 ("Over time scales of 10 to 20 years, the global temperature response to a year's worth of current emissions of SLCFs is at least as large as that due to a year's worth of CO_2 emissions (*high confidence*).").

[9] United Nations Environment Programme & World Meteorological Organization (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone, 254, 262 ("Evaluating global mean temperature change, it was found that the targeted measures to reduce emissions of methane and BC could greatly reduce warming rates over the next few decades (Figure 6.1; Box 6.1). When all measures are fully implemented, warming during the 2030s relative to the present would be only half as much as in the reference scenario. In contrast, even a fairly aggressive strategy to reduce CO_2 emissions, as for the CO_2-measures scenario, does little to mitigate warming until after the next 20-30 years (Box 6.2)."; "Large impacts of the measures examined here were also seen for the Arctic despite the minimal amount of emissions currently taking place there. This occurs due to the high sensitivity of the Arctic both to pollutants that are transported there from remote sources and to radiative forcing that takes place in areas of the northern hemisphere outside the Arctic. The 16 measures examined here, including the measures on pellet stoves and coal briquettes, reduce warming in the Arctic by 0.7 ºC (range 0.2 to 1.3 ºC) at 2040. This is a large portion of the 1.1 ºC (range 0.7 to 1.7 ºC) warming projected under the reference scenario for the Arctic, and hence implementation of the measures would be virtually certain to substantially slow, but not halt, the pace of Arctic climate change."). *See also* Shindell D., *et al.* (2012) *Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security*, Science 335(6065): 183–189, 184–185 ("The global mean response to the CH_4 plus BC measures was –0.54 ± 0.05ºC in the climate model. …Roughly half the forcing is relatively evenly distributed (from the CH_4 measures). The other half is highly inhomogeneous, especially the strong BC forcing, which is greatest over bright desert and snow or ice surfaces. Those areas often exhibit the largest warming mitigation, making the regional temperature response to aerosols and ozone quite distinct from the more homogeneous response to well-mixed greenhouse gases…. BC albedo and direct forcings are large in the Himalayas, where there is an especially pronounced response in the Karakoram, and in the Arctic, where the measures reduce projected warming over the next three decades by approximately two thirds and where regional temperature response patterns correspond fairly closely to albedo forcing (for example, they are larger over the Canadian archipelago than the interior and larger over Russia than Scandinavia or the North Atlantic)."); *and* Naik V., *et al.* (2021) *Chapter 6: Short-lived climate forcers*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 6-7 ("Across the SSPs, the collective reduction of CH_4, ozone precursors and HFCs can make a difference of global mean surface air temperature of 0.2 with a very likely range of [0.1–0.4] °C in 2040 and 0.8 with a very likely range of [0.5–1.3] °C at the end of the 21st century (comparing SSP3-7.0 and SSP1-1.9), which is substantial in the context of the Paris Agreement. Sustained methane mitigation, wherever it occurs, stands out as an option that combines near- and long-term gains on surface temperature (high confidence) and leads to air quality benefits by reducing surface ozone levels globally (high confidence). {6.6.3, 6.7.3, 4.4.4}").

[10] *See* Taillant J. D. (2022) *The Climate Equity Paradox: Time, Key Pollutants and Fast Climate Action to Ensure Intergenerational Climate Equity*, Discussion Paper for the Experts Meeting on Intergenerational Public Goods.

[11] Patt A., *et al.* (2022) *Chapter 14: International cooperation*, *in* Climate Change 2022: Mitigation of Climate Change, *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Shukla P. R., *et al.* (eds.), 14-59 ("Compared with climate hazards, many fewer studies have examined SRM risks—the potential adverse consequences to people and ecosystems from the combination of climate hazards, exposure and vulnerability—or the potential for SRM to reduce risk (Curry et al. 2014; Irvine et al. 2017). Risk analyses have often used inputs from climate models forced with stylized representations of SRM, such as dimming the sun. Fewer have used inputs from climate models that explicitly simulated injection of gases or aerosols into the atmosphere, which include more complex cloud-radiative feedbacks. Most studies have used scenarios where SAI is deployed to hold average global temperature constant despite high emissions.").

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[12] Patt A., *et al.* (2022) *Chapter 14: International cooperation*, *in* CLIMATE CHANGE 2022: MITIGATION OF CLIMATE CHANGE, *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Shukla P. R., *et al.* (eds.), 14-60 ("There is a general lack of research on the wide scope of potential risk or risk reduction to human health, wellbeing and sustainable development from SRM and on their distribution across countries and vulnerable groups (Carlson et al. 2020; Honegger et al. 2021a).").

[13] Kats G. & Glassbrook K. (2020) DELIVERING URBAN RESILIENCE, Smart Surfaces Coalition, 26 ("The importance of making smart roof choices, decreasing urban heat islands (UHI), and improving air quality is especially significant for low-income populations. The publication, Environmental Health Perspectives notes, "Substantial scientific evidence gained in the past decade has shown that various aspects of the built environment can have profound, directly measurable effects on both physical and mental health outcomes, particularly adding to the burden of illness among ethnic minority populations and low-income communities."8 Many roofs in low-income city areas have low solar reflectance, meaning they absorb the majority of sunlight, which greatly increases the heat gain on the top floor of buildings and contributes to higher urban temperatures. In addition, urban low-income residents are more likely to live in areas with no tree canopy and/or greater than 50 percent impervious area.9 The urban poor suffer disproportionally from UHIs (urban heat island) due to their increased likelihood of residing in inefficient homes and attending inefficient schools.").

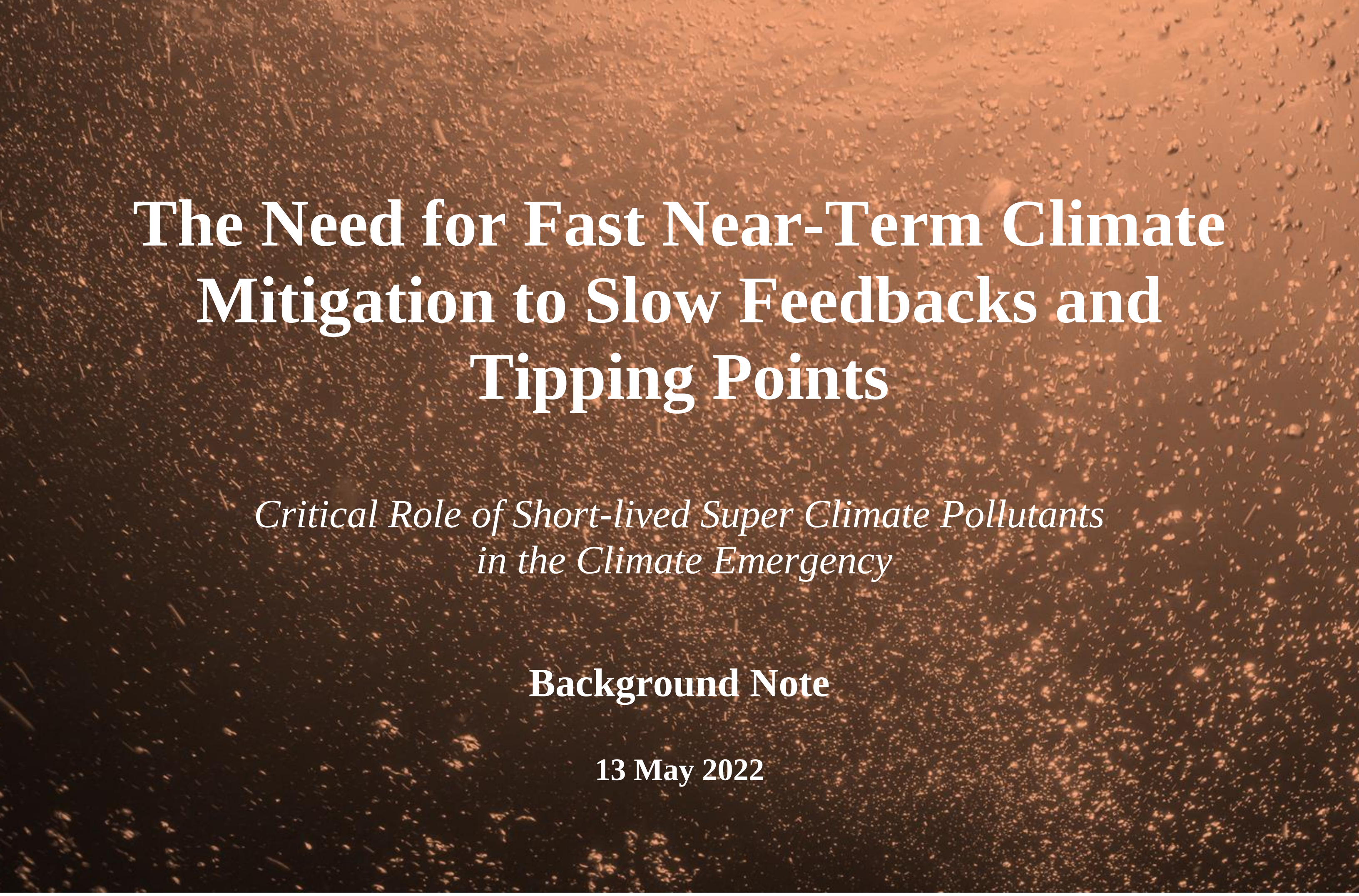
[14] Savaresi A. & Setzer J. (2021) *Rights-based litigation in the climate emergency: mapping the landscape and new knowledge frontiers*, J. HUM. RIGHTS ENVIRON.

[15] 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.").

[16] *See* Taillant J. D. (2022) *The Climate Equity Paradox: Time, Key Pollutants and Fast Climate Action to Ensure Intergenerational Climate Equity*, Discussion Paper for the Experts Meeting on Intergenerational Public Goods.

[17] Art. 3, United Nations Universal Declaration of Human Rights ("Everyone has the right to life, liberty and security of person.").

[18] Greenfield N. (26 April 2022) *Lithium Mining Is Leaving Chile's Indigenous Communities High and Dry (Literally)*, NATURAL RESOURCES DEFENSE COUNCIL.



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

13 May 2022

Institute for Governance
& Sustainable Development (IGSD)

Center for Human Rights and
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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_2 climate pollutants, protect sinks, and enhance urban albedo with smart surfaces, as a complement to cuts in CO_2. It is essential to reduce both non-CO_2 pollutants and CO_2, 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_2.

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

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

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

Institute for Governance
& Sustainable Development

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

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13 May 2022

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1. Introduction and summary

This *Background Note* summarizes the science supporting the need for fast climate mitigation to slow warming in the near term (2022–2041). It also describes the importance of cutting short-lived climate pollutants and protecting sinks in order to slow self-reinforcing feedbacks and avoid tipping points. It explains why winning a fast mitigation sprint to 2030 is critical for addressing the climate emergency and how the sprint complements the marathon to decarbonize the economy and achieve net-zero emissions.

In addition to zeroing out CO_2 emissions to curb long-term warming, it's essential to slow near-term warming in the next two decades by reducing short-lived climate pollutants (SLCPs)—methane (CH_4), black carbon (BC) soot, tropospheric ozone (O_3), and hydrofluorocarbons (HFC). (These short-lived pollutants are often referred to as "super pollutants" because of their potency and ability to quickly reduce warming.)

Cutting SLCP super pollutants can slow warming one to two decades sooner than CO_2-focused strategies alone, avoid two to six times more warming at 2050 than CO_2 cuts can,[1] and reduce projected warming in the Arctic by two-thirds and the rate of global warming by half.[2]

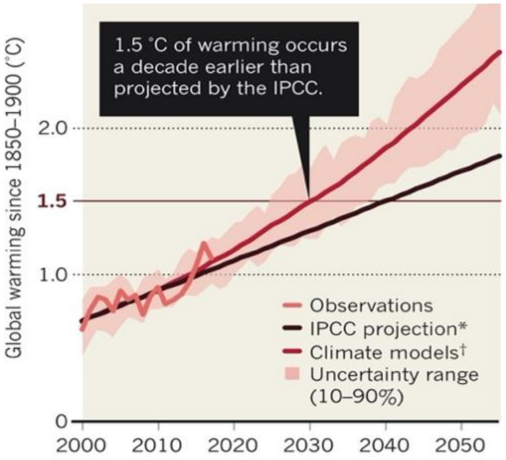
Reducing SLCPs is the only way to cut the rate of warming in the near-term, slow self-reinforcing feedbacks, and avoid irreversible tipping points. In addition to winning a fast mitigation sprint to 2030 by reducing SLCPs, it also is critical to win the marathon to decarbonize the economy, achieve net-zero CO_2 emissions by 2050, and stabilize the climate in the long-term.

- Climate change presents two challenges, or races, that we must simultaneously win: the need to stabilize the climate in the longer-term, and the need to slow the rate of warming in the near-term to reduce the risk of climate extremes that scale with the rate of warming and threaten to accelerate feedbacks and trigger a cascade of irreversible tipping points.
- Achieving 2050 Net Zero CO_2 targets is essential for stabilizing the climate by the end of the century due to the long lifetime of CO_2 in the atmosphere, but cannot by itself prevent global temperatures from exceeding 1.5 °C above pre-industrial levels, the guardrail beyond which the world's climate is expected to pass irreversible tipping points.
    - Indeed, decarbonization alone would be unlikely to stop temperatures exceeding even the much more dangerous 2 °C limit.[3]
- Reducing near-term risks requires pairing CO_2-focused strategies with strategies that reduce the short-lived super climate pollutants 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.
- Addressing the near-term climate emergency requires selecting fast mitigation solutions[4] that provide the most avoided warming in the shortest period of time over the next decade or two; slow the self-reinforcing feedbacks and avoid tipping points;[5] and protect the most vulnerable people and ecosystems[6] from the heat, drought, flooding, and other extremes that will dramatically increase in severity and frequency with every increment of additional warming.[7]
- *Only a dual assault on CO_2 and SLCPs, particularly methane, would make it possible for the world to keep the 1.5 °C guardrail in sight and stay below 2 °C.*
    - These strategies are complementary and not exchangeable.

The window for effective mitigation to slow feedbacks and avoid tipping points is shrinking to perhaps 10 years or less,[8] including the window to prevent crashing through the 1.5 °C guardrail.[9]

- The world could hit the 1.5 °C guardrail by the early 2030s due to rising emissions, declining particulate air pollution that unmasks existing warming, and natural climate variability (Figure 1).[10]
    - The probability of exceeding 1.5 °C by 2026 for at least one year has doubled since 2020, with a likely-as-not (48%) chance that at least one year could be 1.5 °C warmer, according to the World Meteorological Organization.[11]
- The Earth is trapping twice as much heat as it did in 2005, with loss of reflective sea ice and changes in clouds contributing significantly to the extra heat the planet is now retaining.[12]
    - Climate-driven changes in clouds act as a self-reinforcing feedback leading to more warming and higher climate sensitivity.[13]
- Even at 1.1–1.2 °C of global warming in 2020–2021,[14] weather extremes are becoming more frequent and more severe.
    - According to AR6 WGI, "[i]t is *virtually certain* that hot extremes (including heatwaves) have become more frequent and more intense across most land regions since the 1950s... with *high confidence* that human-induced climate change is the main driver of these changes."[15]
    - The record-breaking June 2021 heatwave in the Pacific Northwest (U.S. and Canada) would have been virtually impossible absent human-caused climate change,[16] and would have been much less severe to human health.[17] The probability of such heat waves will increase by up to 200 times by the 2040s, occurring every 5 to 10 years, given our current emissions trajectory.[18]
    - Global warming made the 2019 heatwaves in Western Europe up to 100 times more likely.[19] As Europe sizzled under another heatwave in 2021, the Mediterranean region was evolving into a "wildfire hotspot."[20]
    - With unprecedented long-duration heatwaves afflicting over a billion people in India and Pakistan in 2022, scientists note that "the current climate has changed so significantly that the pre-industrial world becomes a poor basis of comparison."[21]

Figure 1. Projected warming



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

- The probability of "record-shattering" climate extremes "depends on warming rate, rather than the global warming level, and is thus pathway-dependent."[22]
    - According to the National Oceanic and Atmospheric Administration, "[t]he seven warmest years since 1880 have all occurred since 2014, while the 10 warmest years have occurred since 2005."[23] Continued record greenhouse gas (GHG) emissions mean that the rate of warming could increase from 0.2 °C per decade to 0.25–0.32 °C per decade over the next 25 years.[24]
    - Greenhouse gas concentrations in the atmosphere continue to increase at record rates despite the pandemic and economic slowdown.
        - Atmospheric methane concentrations set records in 2020 and 2021 for the fastest rate of increase since records started in 1983 and preliminary data shows methane exceeding 1,900 parts per billion (ppb) for the first time in September 2021.[25] In 2020, the annual increase in atmospheric methane was 15.3 ppb, and in 2021 the annual increase was 17 ppb.[26]
        - Global atmospheric CO_2 concentrations reached a new high of 420 parts per million (ppm) in April 2022, a 50% increase over pre-industrial levels[27] and 2.5 ppm higher than 2020. For comparison, the average increase of CO_2 was 1.5 ppm/year in the 1990s.[28]
- The recent AR6 reports confirm that cutting fossil fuel emissions—the main source of CO_2—by decarbonizing the energy system and shifting to clean energy, *in isolation*, actually makes global warming worse in the short term. This is because burning fossil fuels also emits sulfate aerosols, which act to cool the climate. These cooling sulfates fall out of the atmosphere fast, while CO_2 lasts much longer, thus leading to overall warming for the first decade or two.[29]

According to the Intergovernmental Panel on Climate Change (IPCC), keeping the planet livable by limiting warming to 1.5 °C with no or limited overshoot requires reducing global human-caused methane emissions by 34% in 2030 and 44% in 2040 relative to modelled 2019 levels, in addition to cutting global CO_2 emissions in half in 2030 and by 80% in 2040, and deep cuts to other SLCPs and nitrous oxide.[30]

- AR6 WGIII further finds that "[d]eep GHG emissions reductions by 2030 and 2040, particularly reductions of methane emissions, lower peak warming, reduce the likelihood of overshooting warming limits and lead to less reliance on net negative CO_2 emissions that reverse warming in the latter half of the century… Due to the short lifetime of CH_4 in the atmosphere, projected deep reduction of CH_4 emissions up until the time of net zero CO_2 in modelled mitigation pathways effectively reduces peak global warming. (*high confidence*)"[31]
- These findings build on the conclusions of the IPCC's Special Report on Global Warming of 1.5 °C that identified the three strategies that are essential for keeping the planet livable:
    i. reaching net zero CO_2 by mid-century;
    ii. making deep cuts to SLCPs super pollutants in the next decades; and
    iii. removing up to 1,000 billion tons of CO_2 from the atmosphere by 2100.[32]

Of these three strategies, cutting SLCPs can slow warming one to two decades sooner than CO_2-focused strategies alone, avoid two to six times more warming at 2050 than CO_2 cuts can,[33] and reduce projected warming in the Arctic by two-thirds and the rate of global warming by half.[34]

Box 1. Time and temperature methane metrics: GWP$_{20}$ is an improvement, temperature is even better!

Reducing the risks associated with accelerating warming requires mitigation strategies, like cutting methane emissions, that can slow warming in the near term. Assessing how strategies affect near-term warming requires considering individual emissions by pollutant in units of mass, as required under United Nations Framework Convention on Climate Change (UNFCCC) reporting guidelines and recommended by climate scientists.[35] It also requires accounting for co-emissions by source because policies act on sources, not on individual pollutants.

An ideal option for assessing temperature impact is to convert emissions by source in terms of pollutant and co-emissions to temperature impacts using tools such as the Assessment of Environmental and Societal Benefits of Methane Reductions Tool or the CCAC Temperature Pathway Tool. Alternatively, when comparing climate impacts for short-lived climate pollutants like methane, using the 20-year global warming potential (GWP$_{20}$) better captures near-term warming impact than the 100-year GWP, in addition to being more aligned with meeting the 1.5 °C target.[36] While the UNFCCC currently requires using the GWP$_{100}$ metric when reporting aggregated emissions or removals—which systematically undervalues the climate impact of methane—reporting Parties may use other metrics in addition, such as GWP$_{20}$ or absolute temperature potentials.[37] AR6 updated the metrics for methane as follows: GWP$_{20}$ is 81.2 and GWP$_{100}$ is 27.9.[38] Table 1 below summarizes GWP values for methane from IPCC reports.

Table 1. GWP values for methane from IPCC reports

		AR6	**AR5**		**AR4**	**TAR**	**SAR**
Methane (CH_4)	**GWP$_{20}$**	81.2 (Table 7.SM.7)	84 (Table 8.A.1)	86* (Table 8.7)	72 (Table 2.14)	62 (Table 6.7)	56 (Table 2.9)
	GWP$_{100}$	27.9 (Table 7.SM.7)	28 (Table 8.A.1)	34* (Table 8.7)	25 (Table 2.14)	23 (Table 6.7)	21 (Table 2.9)
Fossil CH_4	**GWP$_{20}$**	82.5 ± 25.8 (Table 7.15)	85 (Table 8.A.1)		--	--	--
	GWP$_{100}$	29.8 ± 11 (Table 7.15)	30 (Table 8.A.1)		--	--	--
Non-fossil CH_4	**GWP$_{20}$**	80.8 ± 25.8 (Table 7.15)	--		--	--	--
	GWP$_{100}$	27.2 ± 11 (Table 7.15)	--		--	--	--

* with carbon cycle feedback. All methane AR6 values include carbon cycle feedback.
AR6 = 2021 Sixth Assessment Report Working Group I; **AR5** = 2013 Fifth Assessment Report Working Group I; **AR4** = 2007 Fourth Assessment Report; **TAR** = 2001 Third Assessment Report; **SAR** = 1995 Second Assessment Report.

Box 1, *continued*

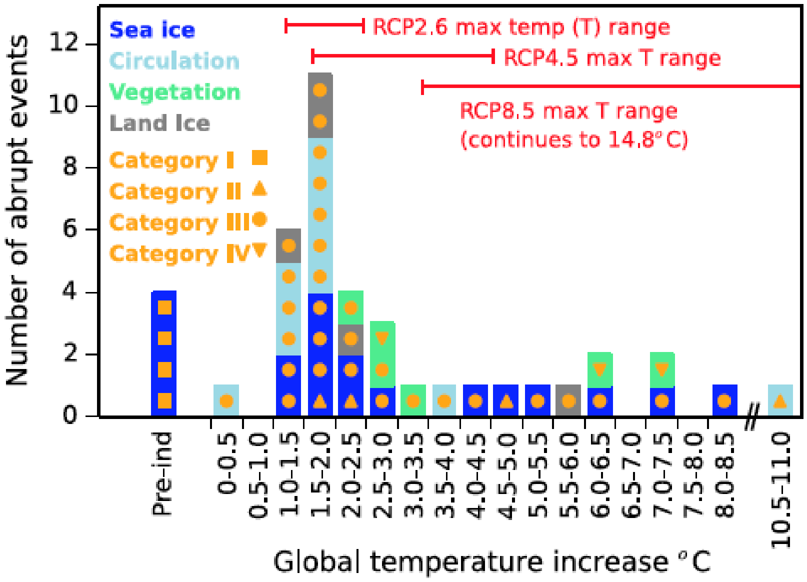
Most aggregation metrics are designed for comparison with long-lived CO_2. Metrics such as CO_2-equivalence in terms of GWP and GWP* are based on mathematical relationships that are intended to make short-lived pollutants like methane comparable to the longer-term warming impact of CO_2 emissions.[39] These aggregate metrics generally ignore co-emitted pollutants with significant near-term climate impacts such as cooling aerosols. The GWP* metric seeks to account for the shorter lifetime of methane by differentiating historical emissions from changes in the rate of emissions.[40] One criticism of this approach is that it essentially "grandfathers" historical emissions, so when applied at the scale of regional or individual methane emitters, sources with high historical emissions can claim negative GWP* by reducing their rate of emissions. This is the case even if their emissions in a given year are equivalent to a new source with no historical emissions. This has led to misuse of these metrics to claim that some sectors with large historical emissions and stable or decreasing current rates of emissions have contributed less to global warming.[41]

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

2. Feedbacks and tipping points are key to understanding 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 1 °C of warming and the 1.5 °C of warming expected in the next decade, with another eleven tipping points projected between 1.5 °C and 2 °C (Figure 2).[42] Domino-like interactions among these systems are projected to lower thresholds and increase the risk of triggering a global cascade of tipping points (Figure 3).[43] Additional as-yet-undiscovered tipping points are possible due to limitations in current models and exclusion of processes such as those related to permafrost and other biogeochemical feedbacks.[44]

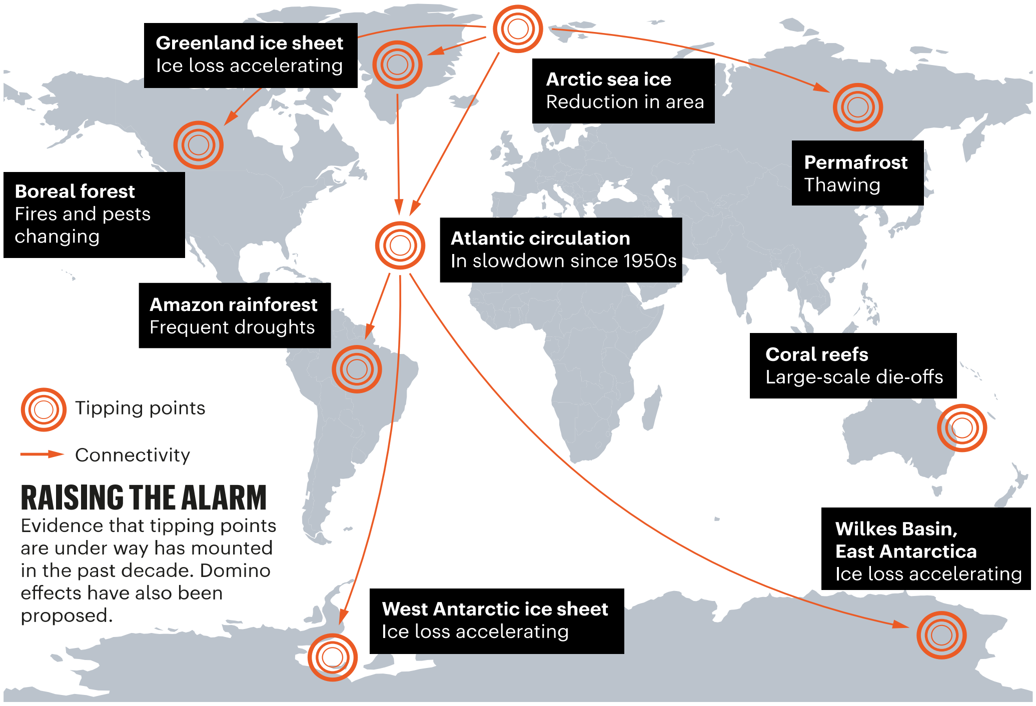
Figure 2. Abrupt climate changes as global temperatures increase



Source: 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, Figure 4.

- The "evidence from tipping points alone suggests that we are in a state of planetary emergency: both the risk and urgency of the situation are acute…."[45]
  - Even with a 1.5 °C overshoot where the temperature limit is only temporarily breached, some of the impacts will be irreversible, even if warming is reduced.[46]
- Self-reinforcing feedbacks, including the loss of Arctic sea ice, are among the most vulnerable links in the chain of climate protection.[47]

Figure 3. Climate tipping points



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

3. Shrinking Arctic shield

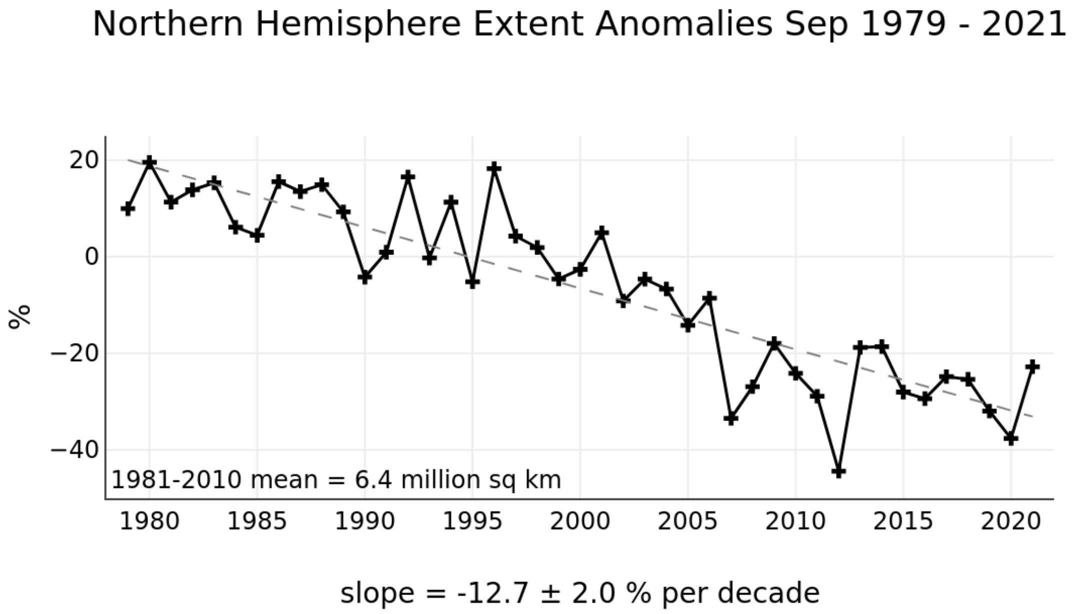
Over the past several decades, the Arctic air temperature has been warming at four times the global average.[48] As a result, the extent of Arctic sea ice—a white shield reflecting incoming solar radiating safely back to space—is shrinking,[49] as is the land-based snow and ice.[50]

A. Disappearing Arctic sea ice

- Arctic sea ice is declining at an accelerating rate.
    - 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.[51]
    - "The rate of ice sheet loss increased by a factor of four between 1992–1999 and 2010–2019."[52]
    - "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 ± 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."[53]
    - The rate of decline in Arctic sea ice thickness from 2002 to 2018 may be underestimated by 60–100% in four of the seven marginal seas, according to a recent study using "snow data with more realistic variability and trends."[54]
    - Multi-year Arctic sea ice is rapidly disappearing, with first-year ice now comprising about 70% of March 2020 ice cover.[55]

- A “New Arctic.”[56]
    - Arctic heatwaves have become as likely, if not more, as heat waves near the equator.[57]
    - Arctic mean surface temperatures may rise by up to 10 °C by the end of the century above the 1985–2014 average.[58]
    - Already in 2020, Siberia experienced heat extremes that would have been “almost impossible” without human-caused global warming, including the first 100 °F temperature recorded north of the Arctic Circle, and record-breaking 118 °F ground temperature, with similar extremes being observed in the first half of 2021.[59]
    - The 15 Septembers with the least Arctic sea ice extent have all been in the last 15 years; on 15 September 2020, the Arctic sea ice reached its annual minimum as the second lowest extent in the satellite record.[60] The 16 September 2021 is the 12th lowest ice minimum on record, with one of the lowest recorded levels of multi-year ice.
    - The Arctic’s “Last Ice Area,” the Wandel Sea, saw unprecedented sea ice loss in August 2020 primarily due to abnormal weather patterns and warmth from the exposed ocean surfaces.[61] Summer sea ice in this area north of Greenland was thought to be more resilient and expected to persist decades longer than rest of the Arctic,[62] providing a refuge for the region’s ice-dependent flora and fauna.[63]
    - Reduced Arctic snow cover is increasing risk of wildfires, which emit black carbon, another super climate pollutant, while destroying sinks and emitting CO_2;[64] wildfires and permafrost thawing can “act together to expose and transfer permafrost C to the atmosphere very rapidly.”[65]
    - In 2021, wildfires around the world emitted an estimated 1.7 billion tons of carbon, roughly equivalent to half of the total annual CO_2 emissions of the European Union.[66] In addition to its massive carbon contribution, wildfires also destroyed carbon sinks that are critical to reducing the level of CO_2 in the atmosphere.
- The Arctic could become nearly ice-free in September within a decade, further reducing its heat-reflecting ability.[67]
    - Most of the Arctic sea ice might become thin (less than 0.5m) during September as early as 2025,[68] or possibly earlier given underestimates of current rates of thinning.[69]
    - 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.[70]
    - The Barents Sea and Greenland Sea could become ice-free year-round by the end of the century under high emissions scenarios.[71]
- In the extreme case when all Arctic sea ice is lost for the sunlit months, climate forcing equivalent to one trillion tons of CO2 would be added to the climate system—on top of the forcing from the 2.4 trillion tons of CO_2 added in the 270 years since the Industrial Revolution—, advancing warming by 25 years.[72]
    - This additional warming would be the equivalent of adding 56 ppm of CO_2 to the current CO_2 concentration,[73] which reached a seasonal peak of 419 ppm in May 2021.[74]
    - The added forcing in the Arctic would be 21 W/m^2; averaged globally this would equal 0.71 W/m^2 of global forcing,[75] compared to the 2.16 W/m^2 added by anthropogenic emissions of CO_2 since the Industrial Revolution.[76]

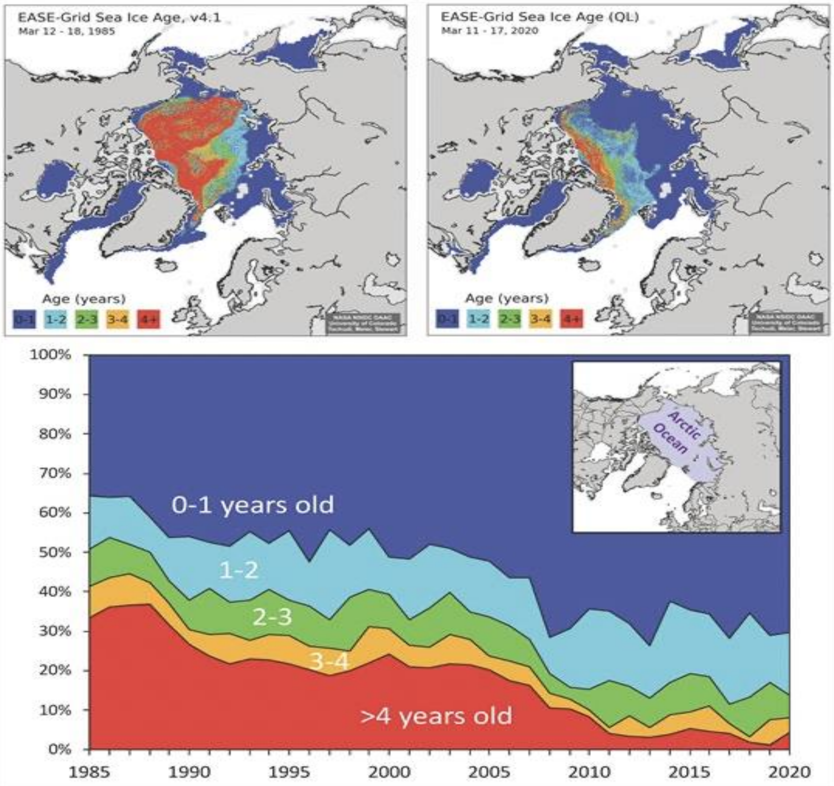
Figure 4. Monthly sea ice extent anomalies



Source: National Snow and Ice Data Center, *Sea Ice Index*, "Monthly Sea Ice Extent Anomaly Graph" (*last visited* 10 May 2022) ("This graph shows monthly ice extent anomalies plotted as a time series of percent difference between the extent for the month in question and the mean for that month based on the January 1981 to December 2021 data. The anomaly data points are plotted as plus signs and the trend line is plotted with a dashed grey line.").

- If all of the cloud cover over the Arctic dissipates along with the loss of all sea ice, the added Arctic warming could be three times as much—the equivalent of three trillion tons of CO_2; in contrast, even if clouds increase to create completely overcast skies over the Arctic, the warming would still add the equivalent of 500 billion tons of CO_2 to the atmosphere.[77]
- 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 about 70% of the ice pack.[78]
  - Less sea ice in the Arctic Ocean allows ocean waves to grow larger, allowing for an acceleration of ice breakup and retreat.[79]
  - The winter of 2020/21 was characterized by exceptionally high wind forcing that resulted in the record loss of the Arctic's multi-year ice driven into the Beaufort Sea,[80] "where ice increasingly can't survive the summer."[81]
  - Arctic warming also leads to a greater number of cyclones and to more intense cyclones,[82] which contribute to Arctic sea ice decline and vice-versa.[83]
  - 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.[84]
  - Warmer oceans are also accelerating sea ice loss, with warmer Pacific waters transporting "unprecedented quantities of heat" into the Arctic Ocean.[85]

Figure 5. Late winter sea ice in the 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, 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).").

B. Disappearing land-based snow and ice

With the Arctic warming at four times the global average, it also is melting land-based snow and ice, which will add about the same amount of warming as the loss of the sea ice, according to Dr. Peter Wadhams:[86]

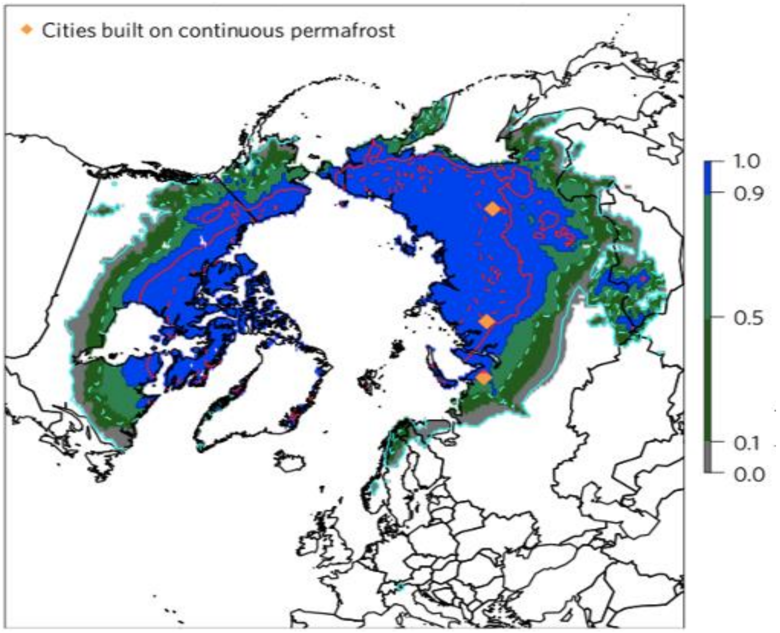
- The loss of reflective land-based snow and ice is "of the same magnitude as the sea ice negative anomaly during the same period, and the change in albedo is roughly the same between snow-covered land and snow-free tundra as it is between sea ice and open water."
- "[T]he similarity of the magnitudes means that snowline retreat and sea ice retreat are each adding about the same amount to global warming."

4. Permafrost emissions of CO_2, CH_4, and N_2O

The accelerated Arctic warming risks triggering another self-reinforcing feedback—permafrost thaw[87]— which would further amplify warming by releasing CO_2 and methane (CH_4),[88] as well as nitrous oxide (N_2O), which also destroys stratospheric ozone.[89]

- Between 2007 and 2016, globally averaged permafrost ground temperature increased by 0.29 °C. Within that period, permafrost in mountains warmed by 0.19 °C and in Antarctica by 0.37 °C.[90]
- The amount of carbon stored in permafrost is nearly twice what is already in the atmosphere—1,700 Gt (gigatons) carbon in permafrost versus 850 Gt carbon in the atmosphere.[91]
    - Record high temperatures have been observed in the upper layer of permafrosts, with sites recording more than a 1 °C increase from 1978 levels.[92]
    - AR6 WGI assesses that the permafrost CO_2 feedback per degree of global warming can be as high as 41 PgC $°C^{-1}$ through 2100. Additionally, methane emissions from permafrost thaw are projected to be up to 19 $GtCO_2e$ $°C^{-1}$ [5.3 PgC_{eq} $°C^{-1}$] by 2100; and beyond 2100, the magnitude of the permafrost carbon feedback strengthens under a high-emissions scenario.[93]
    - Of the approximately 15 million square kilometers of permafrost on land,[94] 3.4 million square kilometers have already thawed; and with warming of 1.5 °C approaching, another 4.8 million square kilometers could thaw gradually.[95]
    - Under the no-mitigation RCP8.5 scenario, gradual permafrost thaw alone could release as much CO_2 as the remaining carbon budget for a likely chance of remaining below 1.5 °C by the end of the century.[96]
    - However, 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" by 40%.[97]
    - Moreover, thawing subsea permafrost beneath the Arctic Ocean could add 20% more emissions by 2100 under an RCP8.5 scenario according to expert judgement.[98]
    - Carbon budgets for pathways targeting 1.5 or 2 °C this century underestimate potential permafrost feedbacks, where a 0.5 °C overshoot could result in a two-fold increase in emissions from permafrost thaw.[99]
    - In addition to accelerating permafrost thaw, heatwaves in the Siberian Arctic in 2020 that peaked at 6 °C above normal temperatures may also be causing fossil methane gas to leak from rock formations.[100]
- If permafrost were a country: by 2100, its emissions could equal as much as the cumulative emissions of the United States, yet 82% of IPCC models do not include carbon emissions from permafrost thaw.[101]
- In addition to the permafrost feedback that accelerates warming, losing permafrost impacts human settlements and health:
    - 3.3 million people, 42% of settlements, and 70% of current infrastructure in the permafrost domain is at risk of severe damage due to permafrost thaw by 2050, including 45% of oil and gas production fields in the Russian Arctic.[102]
    - Damage to Russian infrastructure alone due to permafrost thaw could cost $69 billion by 2050.[103]

Figure 6. 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).").

5. Methane from Arctic Shelf

There also is a risk that methane will be emitted from the shallow seabed of the East Siberian Arctic Shelf as the Arctic ocean warms,[104] which would speed up other global warming impacts.[105]

- Measurements in October 2020 by an international expedition on a Russian research vessel are showing elevated methane release from the Arctic Shelf, according to a story by Jonathan Watts in *The Guardian*. The story quotes Swedish scientist Örjan Gustafsson of Stockholm University, stating that the "East Siberian slope methane hydrate system has been perturbed and the process will be ongoing." Analysis of elevated methane measured in the area in 2014 suggest a fossil methane source beneath the seabed that "may be more eruptive in nature."[106]
- 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.[107]

6. Increasing melt rate of Greenland Ice Sheet and destabilization of West Antarctic Ice Sheet

A series of tipping points and feedbacks exists between 1.5 °C and 2 °C,[108] as confirmed by two IPCC Special Reports from October 2018[109] and September 2019.[110] These include loss of Greenland Ice Sheet and destabilization of West Antarctic Ice Sheet.

- Early warning signs suggest the Greenland Ice Sheet is close to a tipping point.[111] Currently, the best estimate of the threshold for irreversible melting of the Greenland Ice Sheet is around 1.6 °C (0.8–3.2 °C).
    - In the past two decades, the melt rate across Greenland increased 250–575%,[112] and the ice discharge from the Greenland Ice Sheet substantially increased; this will likely persist in the coming years.[113]
    - This would contribute 5–7 meters if all of Greenland melted; and while it may take thousands of years to see the full extent of the sea-level rise, the "timescale of melt depends strongly on the magnitude and duration of the temperature overshoot."[114]
- Melting of the Greenland Ice Sheet and parts of Antarctica have tipping points around the 1.5–2 °C threshold that, once triggered, are irreversible even with carbon dioxide removal strategies.[115] AR6 WGI was unable to exclude the possibility of sea level rise of up to 2.3 meters by 2100 due to uncertainties in ice sheet processes.[116]
    - "Greenland and Antarctica recently showed new year-to-date alltime record low levels of ice mass."[117] On 28 July 2021, Greenland experienced a massive melt event that alone would be enough to cover the state of Florida by two inches of water.[118]
    - "On August 14, 2021, rain was observed at the highest point on the Greenland Ice Sheet…. There is no previous report of rainfall at this location (72.58°N 38.46°W), which reaches 3,216 meters (10,551 feet) in elevation."[119]
- The melting of Greenland also contributes to the weakening of the Atlantic Meridional Overturning Circulation (AMOC), which has reached a critical "overturning" stage; the observational data "suggest that this decline may be associated with an almost complete loss of stability of the AMOC over the course of the last century, and that the AMOC could be close to a critical transition to its weak circulation mode." [120]
    - According to AR6 WGI, it is "very likely" the AMOC will weaken in the 21st century, with "medium confidence" that it will not collapse by 2100.[121]
    - The collapse of this system can lead to faster sea level rise along parts of the Eastern United States and Europe, stronger hurricanes in Southeastern United States, and reduced rainfall across the Sahel.[122]
- In West Antarctica, losing the Thwaites glacier, currently the size of Florida or Britain, could raise sea levels by over two feet (65 cm).[123] Once the Thwaites glacier retreats past a ridge 50 km upstream, the retreat of the glacier would "become unstoppable."[124]
    - The Thwaites glacier is already contributing to 4% of sea-level rise.[125] In the last 20 years, the glacier has lost more than 1,000 billion tons of ice and is continuing to lose ice at a rapidly increasing rate.[126]
    - One glaciologist found that the ice shelf buttressing the Thwaites glacier could collapse in as little as five years due to massive fractures caused by warmer ocean water weakening the ice shelf, setting off a "chain-reaction" that could eventually add 2 to 10 feet of sea level rise over centuries.[127]

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,[128] and this will return to the atmosphere on a timescale of decades to centuries after emissions stop.[129] As noted in AR6 WGI:

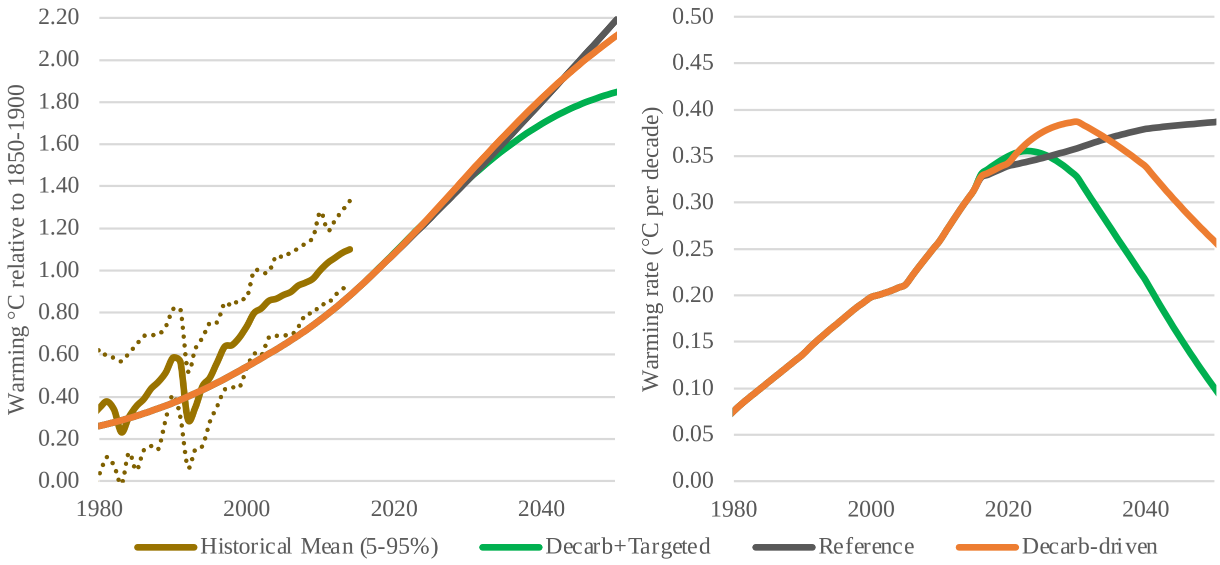
- "It is *virtually certain* that the global ocean has warmed since at least 1971, representing about 90% of the increase in the global energy inventory... and is currently warming faster than at any other time since at least the last deglacial transition (*medium confidence*)... It is *extremely likely* that human influence was the main driver of ocean warming. Ocean warming will continue over the 21st century (*virtually certain*)… [and] is irreversible over centuries to millennia (*medium confidence*)."[130]

8. Limited role of CO_2 mitigation for near-term cooling

Decarbonizing the energy system and achieving net-zero emissions is critical for stabilizing the climate and keeping temperatures below 1.5 °C by the end of this century. However, stopping burning fossil fuels, like coal and diesel, also means cutting co-emitted cooling aerosols. These cooling aerosols fall out of the atmosphere in days to months, and this offsets reductions in warming from decarbonization until around 2050, and likely even accelerates warming over the first decade or more.[131] "The removal of air pollution, either through air quality measures or because combustion processes are phased out to get rid of CO_2, will result in an increase in the resulting rate of warming… The only measures that can counteract this increased rate of warming over the next decades are methane reductions."[132]

- Air pollution that is co-emitted with CO_2 when sulfur-containing coal and oil are burned results in particles that reflect sunlight. These "cooling aerosols" currently "mask" warming of about 0.51 °C; and while the accumulated CO_2 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, unmasking more of the existing warming.[133]
    - The temporary cooling effects of aerosols have been demonstrated in the past. The 1991 Mount Pinatubo eruption injected 15 million tons of sulfur dioxide into the atmosphere, which cooled the planet by 0.5 °C—this cooling effect lasted for nearly two years.[134]
- A previous study found that fast cuts to CO_2 could avoid 0.1 °C of warming by 2050 and up to 1.6 °C by 2100,[135] not accounting for warming due to the unmasking.[136]
    - This would require CO_2 emissions to peak in 2030 and decline by 5.5% per year until carbon neutrality is reached around 2060–2070, after which emissions level off.[137]
    - If CO_2 emissions were to peak in 2020 and decline at 5.5% per year until carbon neutrality is reached around mid-century then level off, this extreme scenario could avoid 0.3 °C of warming by 2050 and up to 1.9 °C by 2100, although unmasking of the cooling aerosol would still lead to net warming in the near term.[138]
    - A separate study found near-term warming within the next two decades of 0.02–0.10 °C due to cuts to fossil fuel CO_2 emissions and associated reductions in cooling aerosols.[139]

Figure 7. Climate temperature response of mitigation strategies focusing only on CO₂ (decarb-driven) compared to decarbonization plus measures targeting SLCPs



(a) Historical and future temperature projections through 2050 for reference scenario (SSP3-7.0), decarbonization-driven mitigation scenario, and an "decarb+targeted" scenario including aggressive decarbonization and targeted SLCP mitigation (adapted from SSP1-1.9). Historical curve (past simulated warming) is from AR6 WGI Figure SPM8.a. (b) Rate of warming (°C per decade) in the reference SSP3, decarbonization only, and "decarb+targeted" mitigation cases.

Source: Dreyfus G. B., Xu Y., Shindell D. T., Zaelke D., & Ramanathan V. (2022) *Mitigation climate disruption in time: A self-consistent approach for avoiding both near-term and long-term global warming*, PROC. NAT'L. ACAD. SCI. (*in press*).

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- and long-term climate protection. These SLCPs also are known as "super climate pollutants." AR6 WGI included a chapter on short-lived climate pollutants for the first time, which finds that "[s]ustained methane mitigation, wherever it occurs, stands out as an option that combines near- and long-term gains on surface temperature (*high confidence*) and leads to air quality benefits by reducing surface ozone levels globally (*high confidence*).… Additional CH_4 and BC mitigation would contribute to offsetting the additional warming associated with SO_2 reductions that would accompany decarbonization (*high confidence*)."[140]

- Cutting SLCPs is the only plausible way to limit warming due to unmasking of cooling aerosols over the next 20 years.[141]
- Accounting for the co-emission of cooling aerosol from fossil fuel burning, a new study finds that strategies focusing exclusively on reducing fossil fuel emissions could result in "weak, near term warming" which could potentially cause temperatures to exceed the 1.5°C level by 2035 and the 2 °C level by 2050. In contrast, the dual strategy that simultaneously reduces the non-carbon dioxide pollutants, especially the short-lived

pollutants, would result in net avoided warming by 2050 four times larger than the net effect of decarbonization alone, and would enable the world to stay well below the 2 °C limit, and significantly improve the chance of remaining below the 1.5 °C guardrail.[142]

- In contrast to the limited amount of warming reduced at 2050 by cutting CO_2 from fossil fuel emissions, fast cuts to SLCPs could avoid up to 0.6 °C of warming by 2050, and up to 1.2 °C by 2100,[143] which would reduce projected warming in the Arctic by two-thirds and the rate of global warming by half.[144]
    - AR6 WGIII finds that limiting warming to 1.5 °C with no or limited overshoot requires deep cuts to SLCPs, in particular reducing methane emissions by 34% in 2030 and 44% in 2040 relative to modelled 2019 and reducing HFC emissions by 85% by 2050 relative to 2019.[145] This re-affirms the conclusion by the IPCC's Special Report on Global Warming of 1.5 °C that cutting SLCPs is essential for staying below 1.5 °C.[146]
    - 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[147]). The 2016 Kigali amendment to phase down HFCs is welcomed."*[148]

    - In their 2021 update, the scientists stress the urgency of "massive-scale climate action" due to growing severity of impacts and risks from "the many reinforcing feedback loops and potential tipping points" and call for "immediate and drastic reductions in dangerous short-lived greenhouse gases, especially methane."[149]

A. Methane (CH_4)

Methane pollution has already caused 0.51 °C of warming, and this will increase if emissions continue to increase, of the total observed warming for 2019 of 1.06 °C (0.88–1.21 °C).[150] As noted by the U.S. White House, "Methane is a potent greenhouse gas and, according to the latest report of the Intergovernmental Panel on Climate Change, accounts for about half of the 1.0 degree Celsius net rise in global average temperature since the pre-industrial era."[151] More leaders are starting to recognize the importance of methane, including former U.S. President Barack Obama, who declared at the 26th Conference of the Parties (COP26) that "curbing methane emissions is currently the single fastest and most effective way to limit warming."[152]

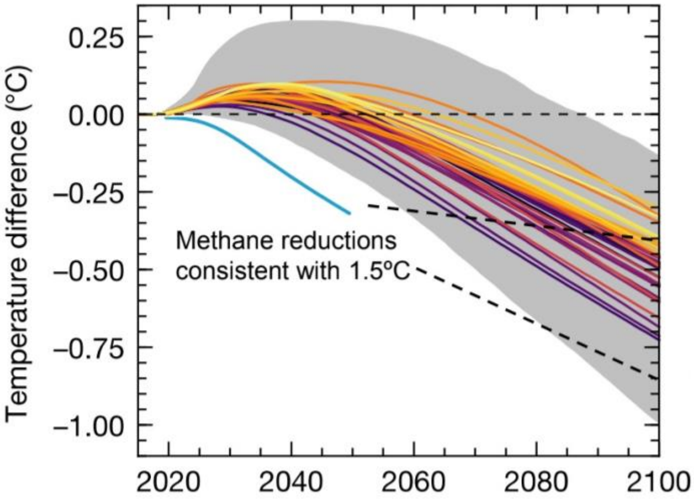
Global Methane Assessment

- Cutting methane emissions is the biggest and fastest strategy for slowing warming and keeping 1.5 °C within reach.[153] A *Global Methane Assessment* (GMA) from the CCAC and UNEP led by Dr. Drew Shindell concludes that available mitigation measures could reduce human-caused methane emissions by 45% by 2030 and avoid nearly 0.3 °C warming by the 2040s.[154]
    - This would prevent 255,000 premature deaths, 775,000 asthma-related hospital visits, 73 billion hours of lost labour from extreme heat, and 26 million tonnes of

crop losses globally (annual value beginning in 2030). Each tonne of methane reduced generates US $4300 in health, productivity, and other benefits.[155] In addition, methane mitigation strategies provide further cost reductions and efficiency gains in the private sector, create jobs, and stimulate technological innovation.

  - Roughly 60% of available targeted measures have low mitigation costs (defined as less than US $21 per tonne of CO_2e for GWP_{100} and US $7 per tonne of CO_2e for GWP_{20}), and just over 50% of those have negative costs.
  - The greatest potential for mitigation is in the oil and gas sector, where the mitigation potential is 812–1,596 Mt/yr of CO_2e for GWP_{100} in 2030; using GWP_{20}, the mitigation is 2,436–4,788 Mt/yr of CO_2e.
  - The waste sector can provide mitigation of 812–1,008 Mt/yr of CO_2e for GWP_{100} in 2030; using GWP_{20}, the mitigation is 2,436–3,024 Mt/yr of CO_2e.
  - The agriculture sector can provide mitigation of 840 Mt/yr of CO_2e for GWP_{100} in 2030; using GWP_{20}, the mitigation is 2,520 Mt/yr of CO_2e.
  - The coal sector can provide mitigation of 336–700 Mt/yr of CO_2e for GWP_{100} in 2030; using GWP_{20}, the mitigation is 1,008–2,100 Mt/yr of CO_2e.
- As the GMA notes, "any action taken to reduce emissions will have an immediate pay off for climate in addition to the current and near-future human health and agricultural production.… Indeed, the expectation that a reduction in emissions will yield quick results, in the order of a decade, is confirmed and emphasizes the importance of methane."[156]
- Fast action to pursue all available methane mitigation measures now could slow the global rate of warming by 30% by mid-century.[157] This is consistent with the 2011 UNEP/WMO Integrated Assessment that showed that fully implementing measures targeting methane and black carbon could halve the rate of global warming and reduce Arctic warming by two-thirds.[158]
  - Strategies to cut methane emissions have 60% more avoided warming in the Arctic than the global average, with the potential to avoid 0.5 °C by 2050.[159]
- AR6 WGII and WGIII confirms the findings of the GMA that "[s]ustained methane mitigation, wherever it occurs, stands out as an option that combines near- and long-term gains on surface temperature (*high confidence*) and leads to air quality benefits by reducing surface ozone levels globally (*high confidence*)." Measures specifically targeting methane are essential, as broader decarbonization measures can only achieve 30% of the needed reductions.[160]
  - The most recent report on climate solutions, AR6 WGIII, reinforces the conclusion that deep and rapid cuts to methane emissions are essential to limiting warming in the near-term and shaving peak warming from overshooting 1.5 °C.[161] Limiting warming to 1.5 °C with little or no overshot requires reducing emissions by 34% below 2019 levels in 2030 and 44% below 2019 levels in 2040.[162]

Figure 8. Methane reductions compared to global mean surface temperature responses to changes in fossil-fuel-related emissions (CO_2 + SO_2)



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

Mitigation and Removal

- Anthropogenic emissions, which make up 60% of total global methane emissions,[163] come primarily from three sectors: energy production (~35%), agriculture (~40%), and waste (~20%).[164] Currently available mitigation measures could reduce emissions from these major sectors by about 180 million metric tonnes of methane per year (Mt/yr), approximately 45%, by 2030.[165]
- 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;[166]
    - Reducing leaks[167] and venting[168] in the oil and gas sector. The Clean Air Task Force states that prohibiting venting of natural gas can reduce emissions by 95%;[169]
    - Eliminating flaring from oil and gas operations, while shifting to clean energy.[170]
    - Improving feeding and manure management on farms. In the U.S., this could cut emissions from manure by as much as 70% and emissions from enteric fermentation by 30%;[171]
    - Upgrading solid waste and wastewater treatment;[172] and
    - Reducing food waste, diverting organic waste from landfills, and improving landfill management, which could reduce landfill emissions in the U.S. by 50% by 2030.[173]
- There also is research underway on the best approach for removing atmospheric methane.[174] This is especially important, as 35 to 50 percent of methane is from natural sources.[175]
    - A modelling study by a Stanford University-led team calculates that removing around three years' worth of human-caused methane emissions would reduce

    - warming by 0.21 °C.[176] The nonprofit Methane Action has stated that removing methane in conjunction with methane emissions reductions can trim an estimated 0.4–0.6 °C of warming.[177]

Global Methane Pledge

- The Global Methane Pledge was formally launched at the high-level segment of COP26 on 2 November 2021.[178] Initially announced by the United States and the European Union at the Major Economies Forum on Energy and Climate hosted by President Biden on 17 September 2021,[179] the Pledge commits governments to a collective goal of reducing global methane emissions by *at least* 30% below 2020 levels by 2030 and moving towards using the highest tier IPCC good practice inventory methodologies to quantify methane emissions, with a particular focus on high emission sources. In addition to the United States and European Union, over 100 initial countries signed on to the pledge, representing 70% of the global economy and nearly half of anthropogenic methane emissions.[180] At least 20 global philanthropic organizations pledged $328 million to support methane reduction efforts.[181]
    - Successful implementation of the Global Methane Pledge would reduce warming by at least 0.2 °C by 2050,[182] and would keep the planet on a pathway consistent with staying within 1.5 °C.[183] This reduction is roughly equivalent to a reduction of 35% below projected 2030 levels. Deploying all available and additional measures, as described in the GMA, could lead to a 45% reduction below 2030 levels to achieve nearly 0.3 °C in avoided warming by the 2040s.[184]

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

B. Black carbon and tropospheric ozone (O_3)

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 CCAC.[185] Black carbon is not a greenhouse gas, but a powerful climate-warming aerosol that is a component of fine particulate matter (specifically, $PM_{2.5}$) that enters the atmosphere through the incomplete combustion of fossil fuels, as well as biofuels and biomass.[186] Fossil fuel combustion is the largest source of air pollution particles and ozone, which kills about 8–10 million[187] people per year. Tropospheric ozone also leads to crop losses of hundreds of million tons or more.[188] 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.[189]

Mitigation

- It is possible to reduce 70% of global black carbon emissions by 2030,[190] including by implementing the following measures:
    - Ensuring fast ratification of the Gothenburg Protocol and the 2012 amendment that includes controls for black carbon;[191]

  - 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;[192]
  - Eliminating flaring, while shifting to clean energy;[193]
  - Switching to clean cooking and heating methods;[194] and
  - Banning heavy fuel oil in the Arctic and establishing black carbon emission standards for vessels by amending Annex VI of the International Convention for the Prevention of Pollution from Ships (MARPOL).[195]
- The Arctic is nearly five times more sensitive to black carbon emitted in the Arctic region than from similar emissions in the mid-latitudes.[196] 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.[197]
  - Heavy-Fuel Oil (HFO) used in shipping is a significant source of black carbon, and the International Maritime Organization (IMO) will ban HFO use in the Arctic beginning in July 2024 for some ships, with waivers and exemptions for others until July 2029.[198] (HFO has been banned in the Antarctic since 2011.[199])
  - Because of the exemptions, the HFO ban will not have a big impact this decade. If the measures that will go into effect in July 2024 had been in effect in 2019, they would have banned only 16% of HFO used in the Arctic, and reduced only 5% of the black carbon.[200] However, if the Arctic HFO ban were imposed without the waivers or exemptions, black carbon emissions could have been reduced by 30%.[201]
  - In 2019, Arctic Council countries set a collective target of reducing black carbon emissions by 25–33% by 2025 compared to 2013 levels.[202] Adopting best available techniques could halve black carbon emissions by 2025 and surpass the current goal.[203] These reductions would improve air quality by reducing exposure of fine particle concentrations from 18 million to 1 million people by 2050 and avoid 40% of air pollution-related deaths in Arctic Council countries by mid-century.[204]
  - In 2021, the IMO adopted a voluntary resolution to reduce black carbon emissions in the Arctic after the annual meeting of the IMO's Marine Environment Protection Committee. In addition to this resolution, the Committee also agreed to revise their GHG Strategy, adopt a voluntary resolution on using cleaner fuel in the Arctic, and address marine plastic litter from ships.[205]
  - Banning investments in oil and gas development in the Arctic can help to further protect the region. All the major U.S. banks—Bank of America, Goldman Sachs, JP Morgan Chase, Wells Fargo, Citi, and Morgan Stanley—have committed not to fund oil and gas exploration in the Arctic.[206] In January 2021, sales of Arctic drilling leases were at an all-time low, mostly due to the public commitments made by major banks.[207] Insurance companies are also starting to commit to banning coverage of Arctic oil projects, including AXA, Swiss RE, and Zurich Insurance.[208]

C. Hydrofluorocarbons (HFCs)

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

Montreal Protocol

- The Montreal Protocol on Substances that Deplete the Ozone Layer (Montreal Protocol) has successfully phased out the production and use of ozone-depleting and potent climate pollutants chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), preventing GHG emissions that otherwise could have equalled or exceeded the emissions of CO_2 in 2010.[209]
    - By end of the century, the Montreal Protocol's steady progress over its 33 years of operation will avoid up to 2.5 °C of warming that otherwise would have already pushed the planet past irreversible tipping points. And this is in addition to achieving its original objective of putting the stratospheric ozone layer on the road to recovery.[210]
        - About 1.7 °C of this avoided warming comes from the Protocol's mandatory reduction of super polluting chemicals—CFCs, HCFCs, and now HFCs—used primarily as refrigerants in cooling equipment.
        - An additional 0.85 °C of warming will be avoided by protecting our planet's forests and other carbon "sinks" from damaging ultraviolet radiation that reduced their ability to pull carbon dioxide out of the atmosphere and store it safely in terrestrial sinks.
- 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.[211]
    - The initial phasedown schedule of the Kigali Amendment would lock-in reductions limiting warming from HFCs in 2100 to about 0.04 °C, avoiding about 90% of the potential, or up to 0.44 °C.[212]
    - Accelerating the phasedown could reduce HFC emissions by an additional 72% in 2050, increasing the chances of staying below 1.5 °C this century.[213]
    - More mitigation is available from: a faster phasedown schedule; collecting and destroying HFCs at end of product life; recycling and destroying HFC "banks" embedded in products and equipment; early replacement of older inefficient cooling equipment using HFC refrigerants; and reducing refrigerant leaks through better design, manufacturing, and servicing.[214]
    - 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.[215]
    - Improving energy efficiency of cooling equipment during the HFC phasedown can more than double the climate benefits in CO_2e by reducing emissions from the power plants that provide the electricity to run the equipment.[216]
    - As of May 2022, there are 131 countries that have accepted, ratified, or approved the Kigali Amendment, including China and India.[217]
    - The U.S. is implementing the Kigali phasedown schedule through the American Innovation and Manufacturing (AIM) Act signed into law in December 2020. The AIM Act and related implementing regulations will reduce the production and consumption of HFCs by 85% by 2036.[218] Twelve states have instituted HFC prohibitions for products and equipment where low-GWP alternatives are available, and six more proposed HFC bans.[219] On 16 November 2021, the White House sent the Kigali Amendment to the Senate for its advice and consent to ratification.[220]

D. Nitrous oxide (N_2O)

While not an SLCP, long-lived nitrous oxide (N_2O) is the most significant anthropogenic ozone-depleting greenhouse gas not yet controlled by the Montreal Protocol.[221] Through mandatory control measures, the Montreal Protocol could spur adoption of technologies to reduce N_2O emissions, which are contributing the equivalent of about 10% of today's CO_2 warming.[222]

Mitigation

- Controlling N_2O emissions could provide climate mitigation of about 1.67 $GtCO_2e$ GWP_{100} by 2050 with 0.94 $GtCO_2e$ from agriculture and about 0.6 $GtCO_2e$ from industry in 2050.[223] In the industrial sector, abatement technology has been available and utilized by manufacturers in developed countries since the 1990s.[224] Moreover, only five countries produce 86% of industrial N_2O: China, the United States, Singapore, Egypt, and Russia.[225]
- In the agriculture sector, several solutions have been found to be cost-effective in reducing N_2O emissions from agricultural processes: precision farming using variable rate technology and nitrogen inhibitors that suppress the microbial activity that produces N_2O. Studies have found that variable rate technology can increase yields by 1–10%, while reducing 4–37% of nitrogen fertilization.[226] Another solution, the SOP product line,[227] stimulates nitrogen-uptake in crops and inhibits GHG emissions from manure.[228] Moreover, allowing continued increase in N_2O emissions while reducing CO_2 and CH_4 emissions could reverse progress on recovery of the stratospheric ozone layer.[229]

10. Strategies for protecting the Arctic and for removing non-CO_2 climate pollutants

Rapid reductions in SLCPs are key to protecting the Arctic. The *Global Methane Assessment* calculated that strategies to cut methane emissions 40–45% by 2030 could avoid nearly 0.3 °C by the 2040s, and 0.5 °C in the Arctic by 2050, 60% more than the global average.[230] The 2011 UNEP/WMO Integrated Assessment of Black Carbon and Tropospheric Ozone calculated that fully implementing measures targeting methane and black carbon could reduce the rate of global warming by half and reduce Arctic warming by two-thirds.[231] Pursuing just the methane mitigation measures would cut the global rate of warming by 30% by mid-century.[232] Rapid reductions in methane emissions could also reduce the risk of losing the reflective summer Arctic sea ice.[233] If Arctic summer sea ice were to disappear for the sunlit months, as could happen as early as mid-century,[234] it would be the warming equivalent of 1,000 billion tonnes of CO_2.[235] A similar amount of warming would be expected from simultaneous loss of the land-based snow and ice.[236]

Additional strategies being investigated for protecting and restoring Arctic ice include enhancing albedo of Arctic sea ice and marine cloud brightening.[237] Strategies also are being investigated for removing methane and other non-CO_2 greenhouse gases from the atmosphere.[238]

- In April 2021, the Department of Energy's Advanced Research Projects Agency–Energy (ARPA-E) announced a $35 million program to reduce methane emissions, called REMEDY (Reducing Emissions of Methane Every Day of the Year). This three-year research program looks to reduce methane emissions from three sources in the oil, gas, and coal sectors. According to ARPA-E, these three sources contribute to at least 10% of U.S. anthropogenic methane emissions.[239] In developing the REMEDY program, ARPA-E recognized the need for further research on methane capture from the air in parallel with efforts to capture CO_2.[240]

- On 2 December 2021, the Department of Energy announced the 12 selectees that would receive $35 million in funding for projects to cut greenhouse gas emissions in oil, gas, and coal sectors. These projects include research on reducing methane emissions from natural gas engines, gas flares, and coal mine shafts.[241]

11. 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_2 provides critical fast mitigation, while also protecting biodiversity.[242] Conservation International estimates that Earth's ecosystems contain 139 billion metric tons (Gt C) [510 $GtCO_2$] of "irrecoverable carbon," defined as carbon stored in natural systems that "are vulnerable to release from human activity and, if lost, could not be restored by 2050." The highest concentrations of irrecoverable carbon are in the Amazon (31.5 Gt C) [115.5 $GtCO_2$], the Congo Basin (8.1 Gt C) [29.7 $GtCO_2$], and New Guinea (7.3 Gt C) [26.8 $GtCO_2$], with additional reserves in boreal forests, mangroves, and peatlands.[243]

- Already, 17% of the Amazon forest has been destroyed, and there is an expected tipping point when 20 to 40% is lost.[244] Continued deforestation and drying in the Amazon under high-emissions scenarios could result in up to a 50% loss in forest cover by 2050.[245]
- Changes to the global water cycle may be pushing the Amazon to a tipping point.[246]
- With increased deforestation, including from fires, greater disturbances, and higher temperatures, there is a point beyond which the Amazon rainforest would be difficult to reestablish,[247] with recent measurements suggesting that the southeastern area of the Amazon has already shifted to a net carbon source as tree mortality increases and photosynthesis decreases.[248]
- Tropical and Boreal forest dieback could contribute up to 200 PgC [733 $GtCO_2$] by 2100.[249]

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,[250] calling into question national pledges under the Paris Accord, which rely heavily on land uptake of carbon to meet mitigation goals.[251]

Nature-based solutions help limit warming in three ways: first, protecting forests and sinks prevents the release of carbon; second, restoring critical forests and sinks sequester carbon; and third, improving land management can both reduce emissions of carbon, methane, and nitrous oxide and sequester carbon.[252] 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;[253]
- Preserving existing peatlands and restoring degraded peatlands;[254]
- Restoring coastal 'blue carbon' ecosystems;[255] and
- Prohibiting bioenergy.[256]

On the second day of COP26, world leaders agreed to halt deforestation by 2030 in the Glasgow Leaders' Declaration on Forests and Land Use. As of May 2022, 141 countries have committed to this agreement, including Brazil, China, Russia, and the United States, covering about 91% of the world's forests.[257] This declaration includes $12 billion in funding for forest-related climate finance between 2021–2025, an additional $7 billion in funding from private companies, and a global roadmap to make 75% of forest commodity supply chains sustainable.[258]

In addition, the U.S. launched a parallel domestic Plan to Conserve Global Forests: Critical Carbon Sinks; this is an "all-of-government effort" to end natural forest loss, preserve global ecosystems, including carbon sinks, and restore at least an additional 200 million hectares of forests and other ecosystems by 2030 with a dedicated fund of $9 billion to support this effort.[259]

12. Conclusion

Global warming is projected to cross the 1.5 °C guardrail as soon as the early 2030s. Policies that rely on decarbonization alone are insufficient to slow the near term warming to keep the Planet even below the more dangerous 2.0 °C threshold. *We need to urgently broaden our approach to climate mitigation to target both carbon dioxide (CO_2) and other largely neglected pollutants to address the near-term and long-term impacts of climate disruption, reduce the risk of crossing irreversible tipping points, and maintain a livable planet*.

Combining efforts to cut CO_2 emissions by decarbonizing the energy system *with* mitigation measures targeting non-CO_2 SLCPs methane, HFC refrigerants, black carbon soot, and ground-level ozone smog, as well nitrous oxide, would reduce the rate of warming by half from 2030 to 2050, which would slow the rate of warming a decade or two earlier than decarbonization alone and *make it possible for the world to stay below the 1.5 ℃ guardrail*.[260]

AR6 is a "code red" for the climate emergency.[261] The IPCC's 2018 Special Report on 1.5 °C presents the three essential strategies for keeping the planet relatively safe: reducing CO_2, reducing SLCPs, and removing up to 1,000 billion tons of CO_2 from the atmosphere by 2100.[262] Cutting SLCPs is the only known strategy that can slow warming and feedbacks in time to avoid catastrophic and perhaps existential impacts[263] from Hothouse Earth,[264] other than perhaps solar radiation management, which carries its own risks.

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

> "*Four shifts in focus reflect this new architecture; first, the near-unanimous recognition of the impending climate emergency and the need to limit warming to 1.5 degrees Celsius; second, the recognition "that 2030 is the new 2050," as French President Emmanuel Macron said, and that major emission cuts have to be made in this decade (note also that the U.S.-China Joint Glasgow Declaration marked the first time that the United States and China acknowledged the urgency of climate action in this "critical decade" of the 2020s); third, the recognition that cutting non-CO2 emissions (particularly methane) is essential for slowing warming in the next couple of decades and that cuts to CO2 alone cannot address the near-term emergency; and fourth, the addition of sector-specific approaches in recognition that it is often more efficient and effective to address individual sectors of the economy in reaching climate solutions*."[265]

References

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[1] Dreyfus G. B., Xu Y., Shindell D. T., Zaelke D., & Ramanathan V. (2022) *Mitigation climate disruption in time: A self-consistent approach for avoiding both near-term and long-term global warming*, Proc. Nat’l. Acad. Sci. (*in press*) (“We find that mitigation measures that target only decarbonization are essential for strong long-term cooling but can result in weak near-term warming (due to unmasking the cooling effect of co-emitted aerosols) and lead to temperatures exceeding 2°C before 2050. In contrast, pairing decarbonization with additional mitigation measures targeting short-lived climate pollutants (SLCPs) and N_2O, slows the rate of warming a decade or two earlier than decarbonization alone and avoids the 2°C threshold altogether. These non-CO_2 targeted measures when combined with decarbonization can provide net cooling by 2030, reduce the rate of warming from 2030 to 2050 by about 50%, roughly half of which comes from methane, significantly larger than decarbonization alone over this timeframe.”); (“Aggressive decarbonization to achieve net-zero CO_2 emissions in the 2050s (as in the decarb-only scenario) results in weakly accelerated net warming compared to the reference case, with a positive warming up to 0.03 °C in the mid-2030s, and no net avoided warming until the mid-2040s due to the reduction in co-emitted cooling aerosols (Figure 3a). By 2050, decarbonization measures result in very limited net avoided warming (0.07°C), consistent with Shindell and Smith (43), but rise to a likely detectable 0.25°C by 2060 and a major benefit of 1.4°C by 2100 (Table S5). In contrast, pairing decarbonization with mitigation measures targeting CH_4, BC, HFC, and N_2O (not an SLCP due to its longer lifetime) independent from decarbonization are essential to slowing the rate of warming by the 2030s to under 0.3°C per decade (Table 1, Figure 3b), similar to the 0.2°C to 0.25°C per decade warming prior to 2020 (38, 53). Recent studies suggest that rate of warming rather than level of warming controls likelihood of record-shattering extreme weather events (54, 55). By 2050, the net avoided warming from the targeted non-CO_2 measures is 0.26°C, almost 4 times larger than the net benefit of decarbonization alone (0.07°C) (Table S5).”). *See also* Xu Y. & Ramanathan V. (2017) Well below 2 °C: Mitigation strategies for avoiding dangerous to catastrophic climate changes, Proc. Nat’l. Acad. Sci. 114(39): 10315–10323, 10321 (“Constrained by CO_2 lifetime and the diffusion time of new technologies (decades), the scenarios considered here (SI Appendix, Fig. S2A) suggest that about half of the 2.6 °C CO_2 warming in the baseline-fast scenario can be mitigated by 2100 and only 0.1–0.3 °C can be mitigated by 2050… The SP [super pollutant] lever targets SLCPs. Reducing SLCP emissions thins the SP blanket within few decades, given the shorter lifetimes of SLCPs (weeks for BC to about 15 years for HFCs). The mitigation potential of the SP lever with a maximum deployment of current technologies … is about 0.6 °C by 2050 and 1.2 °C by 2100 (SI Appendix, Fig. S5B and Table S1).”); *and* Naik V., *et al.* (2021) Chapter 6: Short-lived climate forcers, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 6-6 (“Over time scales of 10 to 20 years, the global temperature response to a year’s worth of current emissions of SLCFs is at least as large as that due to a year’s worth of CO_2 emissions (*high confidence*).”).

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

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greenhouse gases…. BC albedo and direct forcings are large in the Himalayas, where there is an especially pronounced response in the Karakoram, and in the Arctic, where the measures reduce projected warming over the next three decades by approximately two thirds and where regional temperature response patterns correspond fairly closely to albedo forcing (for example, they are larger over the Canadian archipelago than the interior and larger over Russia than Scandinavia or the North Atlantic).”); *and* Naik V., *et al.* (2021) Chapter 6: Short-lived climate forcers, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 6-7 (“Across the SSPs, the collective reduction of CH$_4$, ozone precursors and HFCs can make a difference of global mean surface air temperature of 0.2 with a very likely range of [0.1–0.4] °C in 2040 and 0.8 with a very likely range of [0.5–1.3] °C at the end of the 21st century (comparing SSP3-7.0 and SSP1-1.9), which is substantial in the context of the Paris Agreement. Sustained methane mitigation, wherever it occurs, stands out as an option that combines near- and long-term gains on surface temperature (high confidence) and leads to air quality benefits by reducing surface ozone levels globally (high confidence). {6.6.3, 6.7.3, 4.4.4}”).

[3] Dreyfus G. B., Xu Y., Shindell D. T., Zaelke D., & Ramanathan V. (2022) *Mitigation climate disruption in time: A self-consistent approach for avoiding both near-term and long-term global warming*, Proc. Nat’l. Acad. Sci. (*in press*) (“We find that mitigation measures that target only decarbonization are essential for strong long-term cooling but can result in weak near-term warming (due to unmasking the cooling effect of co-emitted aerosols) and lead to temperatures exceeding 2°C before 2050. In contrast, pairing decarbonization with additional mitigation measures targeting short-lived climate pollutants (SLCPs) and N$_2$O, slows the rate of warming a decade or two earlier than decarbonization alone and avoids the 2°C threshold altogether. These non-CO$_2$ targeted measures when combined with decarbonization can provide net cooling by 2030, reduce the rate of warming from 2030 to 2050 by about 50%, roughly half of which comes from methane, significantly larger than decarbonization alone over this timeframe.”).

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

[5] Lenton T. M., Rockstrom J., Gaffney O., Rahmstorf S., Richardson K., Steffen W., & Schellnhuber H. J. (2019) Climate tipping points—too risky to bet against, Comment, Nature 575(7784): 592–595, 594 (“In our view, the clearest emergency would be if we were approaching a global cascade of tipping points that led to a new, less habitable, ‘hothouse’ climate state[11]. Interactions could happen through ocean and atmospheric circulation or through feedbacks that increase greenhouse-gas levels and global temperature. Alternatively, strong cloud feedbacks could cause a global tipping point[12,13].We argue that cascading effects might be common. Research last year[14] analysed 30 types of regime shift spanning physical climate and ecological systems, from collapse of the West Antarctic ice sheet to a switch from rainforest to savanna. This indicated that exceeding tipping points in one system can increase the risk of crossing them in others. Such links were found for 45% of possible interactions[14]. In our view, examples are starting to be observed. … If damaging tipping cascades can occur and a global tipping point cannot be ruled out,

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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).”).

[6] Xu Y. & Ramanathan V. (2017) Well below 2 °C: Mitigation strategies for avoiding dangerous to catastrophic climate changes, Proc. Nat'l. Acad. Sci. 114(39): 10319–10323, 10320 (“Box 2. Risk Categorization of Climate Change to Society. … [A] 2 °C warming would double the land area subject to deadly heat and expose 48% of the population. A 4 °C warming by 2100 would subject 47% of the land area and almost 74% of the world population to deadly heat, which could pose existential risks to humans and mammals alike unless massive adaptation measures are implemented, such as providing air conditioning to the entire population or a massive relocation of most of the population to safer climates. … This bottom 3 billion population comprises mostly subsistent farmers, whose livelihood will be severely impacted, if not destroyed, with a one- to five-year megadrought, heat waves, or heavy floods; for those among the bottom 3 billion of the world's population who are living in coastal areas, a 1- to 2-m rise in sea level (likely with a warming in excess of 3 °C) poses existential threat if they do not relocate or migrate. It has been estimated that several hundred million people would be subject to famine with warming in excess of 4 °C (54). However, there has essentially been no discussion on warming beyond 5 °C. Climate change-induced species extinction is one major concern with warming of such large magnitudes (>5 °C). The current rate of loss of species is ~1,000-fold the historical rate, due largely to habitat destruction. At this rate, about 25% of species are in danger of extinction in the coming decades (56). Global warming of 6 °C or more (accompanied by increase in ocean acidity due to increased CO_2) can act as a major force multiplier and expose as much as 90% of species to the dangers of extinction (57). The bodily harms combined with climate change-forced species destruction, biodiversity loss, and threats to water and food security, as summarized recently (58), motivated us to categorize warming beyond 5 °C as unknown??, implying the possibility of existential threats.”). *See also* Xu C., Kohler T. A., Lenton T. M., Svenning J.-C., & Scheffer M. (2020) Future of the human climate niche, Proc. Nat'l. Acad. Sci. 117(21): 11350–11355, 11350 (“Here, we demonstrate that for millennia, human populations have resided in the same narrow part of the climatic envelope available on the globe, characterized by a major mode around ~11 °C to 15 °C mean annual temperature (MAT). …We show that in a business-as-usual climate change scenario, the geographical position of this temperature niche is projected to shift more over the coming 50 y than it has moved since 6000 BP. … Specifically, 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).”); and Watts N., *et al.* (2021) The 2020 report of The Lancet Countdown on health and climate change: responding to converging crises, The Lancet 397(10269): 129–170, 129 (“Vulnerable populations were exposed to an additional 475 million heatwave events globally in 2019, which was, in turn, reflected in excess morbidity and mortality (indicator 1.1.2). During the past 20 years, there has been a 53.7% increase in heat-related mortality in people older than 65 years, reaching a total of 296 000 deaths in 2018 (indicator 1.1.3). The high cost in terms of human lives and suffering is associated with effects on economic output, with 302 billion h of potential labour capacity lost in 2019 (indicator 1.1.4). India and Indonesia were among the worst affected countries, seeing losses of potential labour capacity equivalent to 4–6% of their annual gross domestic product (indicator 4.1.3);” *as cited in* Atwoli L., *et al.* (2021) Call for emergency action to limit global temperature increases, restore biodiversity, and protect health, The Lancet 398(10304): 939–941, 939 (“Harms

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disproportionately affect the most vulnerable, including children, older populations, ethnic minorities, poorer communities, and those with underlying health problems.”).

[7] Intergovernmental Panel on Climate Change (2021) Summary for Policymakers, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), SPM-19 (“With every additional increment of global warming, changes in extremes continue to become larger. For example, every additional 0.5°C of global warming causes clearly discernible increases in the intensity and frequency of hot extremes, including heatwaves (*very likely*), and heavy precipitation (*high confidence*), as well as agricultural and ecological droughts in some regions (*high confidence*). Discernible changes in intensity and frequency of meteorological droughts, with more regions showing increases than decreases, are seen in some regions for every additional 0.5°C of global warming (*medium confidence*). Increases in frequency and intensity of hydrological droughts become larger with increasing global warming in some regions (*medium confidence*). There will be an increasing occurrence of some extreme events unprecedented in the observational record with additional global warming, even at 1.5°C of global warming. Projected percentage changes in frequency are higher for rarer events (*high confidence*).”). *See also* Fischer E. M., Sippel S., & Knutti R. (2021) Increasing probability of record-shattering climate extremes, NAT. CLIM. CHANGE 1–7, 1 (“Here, we show models project not only more intense extremes but also events that break previous records by much larger margins. These record-shattering extremes, nearly impossible in the absence of warming, are likely to occur in the coming decades. We demonstrate that their probability of occurrence depends on warming rate, rather than global warming level, and is thus pathway-dependent. In high-emission scenarios, week-long heat extremes that break records by three or more standard deviations are two to seven times more probable in 2021–2050 and three to 21 times more probable in 2051–2080, compared to the last three decades.”).

[8] Lenton T. M., Rockstrom J., Gaffney O., Rahmstorf S., Richardson K., Steffen W., & Schellnhuber H. J. (2019) Climate tipping points—too risky to bet against, Comment, NATURE 575(7784): 592–595, 592 (“Models suggest that the Greenland ice sheet could be doomed at 1.5 °C of warming3, which could happen as soon as 2030. …The world’s remaining emissions budget for a 50:50 chance of staying within 1.5 °C of warming is only about 500 gigatonnes (Gt) of CO_2. Permafrost emissions could take an estimated 20% (100 Gt CO_2) 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_2 and boreal forests a further 110 Gt CO_2. With global total CO_2 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.”). *See also* Ripple W. J., Wolf C., Newsome T. M., Gregg J. W., Lenton T. M., Palomo I., Eikelboom J. A. J., Law B. E., Huq S., Duffy P. B., & Rockström J. (2021) World Scientists’ Warning of a Climate Emergency 2021, BIOSCIENCE: biab079, 1–5, 1 (“There is also mounting evidence that we are nearing or have already crossed tipping points associated with critical parts of the Earth system, including the West Antarctic and Greenland ice sheets, warm-water coral reefs, and the Amazon rainforest.”).

[9] Intergovernmental Panel on Climate Change (2022) *Summary for Policymakers*, *in* CLIMATE CHANGE 2022: IMPACTS, ADAPTATION, AND VULNERABILITY, *Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Pörtner H.-O., *et al.* (eds.), SPM-11, SPM-13 (“Approximately 3.3 to 3.6 billion people live in contexts that are highly vulnerable to climate change (*high confidence*).”; “Levels of risk for all Reasons for Concern (RFC) are assessed to become high to very high at lower global warming levels than in AR5 (*high confidence*). Between 1.2°C and 4.5°C global warming level very high risks emerge in all five RFCs compared to just two RFCs in AR5 (*high confidence*). Two of these transitions from high to very high risk are associated with near-term warming: risks to unique and threatened systems at a median value of 1.5°C [1.2 to 2.0] °C (*high confidence*) and risks associated with extreme weather events at a median value of 2°C [1.8 to 2.5] °C (*medium confidence*). Some key risks contributing to the RFCs are projected to lead to widespread, pervasive, and potentially irreversible impacts at global warming levels of 1.5–2°C if exposure and vulnerability are high and adaptation is low (*medium confidence*).”; “**SPM.B.3** Global warming, reaching 1.5°C in the near-term, would cause unavoidable increases in multiple climate hazards and present multiple risks to ecosystems and humans (*very high confidence*). The level of risk will depend on concurrent near-term trends in vulnerability, exposure, level of socioeconomic development and adaptation (*high confidence*).”).

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[10] Xu Y., Ramanathan V., & Victor D. G. (2018) Global warming will happen faster than we think, Comment, Nature 564(7734): 30–32, 30–31 ("But the latest IPCC special report underplays another alarming fact: global warming is accelerating. Three trends—rising emissions, declining air pollution and natural climate cycles—will combine over the next 20 years to make climate change faster and more furious than anticipated. In our view, there's a good chance that we could breach the 1.5 °C level by 2030, not by 2040 as projected in the special report (see 'Accelerated warming'). The climate-modelling community has not grappled enough with the rapid changes that policymakers care most about, preferring to focus on longer-term trends and equilibria."). Since Xu, Ramanathan, and Victor comment was published, the IPCC has updated its estimate for when 1.5°C will be exceeded: Arias P. A., *et al.* (2021) Technical Summary, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), TS-9 ("Timing of crossing 1.5°C global warming: Slightly different approaches are used in SR1.5 and in this Report. SR1.5 assessed a likely range of 2030 to 2052 for reaching a global warming level of 1.5°C (for a 30-year period), assuming a continued, constant rate of warming. In AR6, combining the larger estimate of global warming to date and the assessed climate response to all considered scenarios, the central estimate of crossing 1.5°C of global warming (for a 20-year period) occurs in the early 2030s, ten years earlier than the midpoint of the likely range assessed in the SR1.5, assuming no major volcanic eruption. (TS.1.3, Cross-Section Box TS.1)"). *See also* Matthews H. D., Tokarska K. B., Rogelj J., Smith C. J., MacDougall A. H., Haustein K., Mengis N., Sippel S., Forster P. M., & Knutti R. (2021) An integrated approach to quantifying uncertainties in the remaining carbon budget, Commun. Earth & Environ. 2: 1–11, 5 ("It is worth noting however, that the spread of our [remaining carbon budget (RCBs)] estimate does include negative values, with a 17% chance that the RCB for 1.5 °C is less than zero (i.e. is already exceeded). This outcome could arise due to current and/or unrealised future warming being at the higher end of their respective distributions, or in the case that the current non-CO_2 forcing fraction is small or negative owing to very strong current aerosol forcing. In this case, we would expect 1.5 °C to be exceeded even in the absence of additional emissions, and any future emissions between now and the time of net-zero CO_2 emissions would cause temperatures to rise further above this threshold.").

[11] Madge G. (8 May 2022) Temporary breaching of 1.5C in next five years?, UK Met Office, Press Release ("The chance of at least one year exceeding 1.5°C above pre-industrial levels between 2022-2026 is about as likely as not (48%). However, there is only a very small chance (10%) of the five-year mean exceeding this threshold."); *discussing* World Meteorological Organization (2022) Global Annual to Decadal Climate Update. *See also* Hook L. (9 May 2022) World on course to breach global 1.5C warming threshold within five years, Financial Times. *For previous years, see* World Meteorological Organization (2021) WMO Global Annual to Decadal Climate Update, 5 ("Relative to pre-industrial conditions, the annual mean global near surface temperature is predicted to be between 0.9°C and 1.8°C higher (90% confidence interval). The chance of at least one year exceeding 1.5°C above pre-industrial levels is 44% and is increasing with time. There is a very small chance (10%) of the five-year mean exceeding this threshold. The Paris Agreement refers to a global temperature increase of 1.5°C, which is normally interpreted as the long-term warming, but temporary exceedances would be expected as global temperatures approach the threshold."); *discussed in* Hodgson C. (26 May 2021) Chance of temporarily reaching 1.5C in warming is rising, WMO says, Financial Times. *Compare with* World Meteorological Organization (2020) United in Science 2020, 16 ("Figure 2 shows that in the five-year period 2020–2024, the annual mean global near surface temperature is predicted to be between 0.91 °C and 1.59 °C above pre-industrial conditions (taken as the average over the period 1850 to 1900). The chance of at least one year exceeding 1.5 °C above pre-industrial levels is 24%, with a very small chance (3%) of the five-year mean exceeding this level. Confidence in forecasts of global mean temperature is high. However, the coronavirus lockdown caused changes in emissions of greenhouse gases and aerosols that were not included in the forecast models. The impact of changes in greenhouse gases is likely small based on early estimates (Le Quéré et al. 2020 and Carbonbrief.org).").

[12] Loeb N. G., Johnson G. C., Thorsen T. J., Lyman J. M., Rose F. G., & Kato S. (2021) Satellite and Ocean Data Reveal Marked Increase in Earth's Heating Rate, Geophys. Res. Lett.: e2021GL093047 ("Marked decreases in clouds and sea-ice and increases in trace gases and water vapor combine to increase the rate of planetary heat uptake.").

[13] Arias P. A., *et al.* (2021) Technical Summary, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), TS-59 ("The net effect of changes in clouds in response to global warming

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

[14] Copernicus Climate Services (10 January 2022) Copernicus: Globally, the seven hottest years on record were the last seven; carbon dioxide and methane concentrations continue to rise (“Globally, 2021 was the fifth warmest year on record, but only marginally warmer than 2015 and 2018; The annual average temperature was 0.3°C above the temperature of the 1991-2020 reference period, and 1.1-1.2°C above the pre-industrial level of 1850-1900; The last seven years have been the warmest years on record by a clear margin”). *See also* National Aeronautics and Space Administration (13 January 2022) 2021 Tied for 6th Warmest Year in Continued Trend, NASA Analysis Shows; National Oceanic and Atmospheric Administration (13 January 2022) 2021 was world’s 6th-warmest year on record; National Aeronautics and Space Administration (14 January 2021) 2020 Tied for Warmest Year on Record, NASA Analysis Shows (“Tracking global temperature trends provides a critical indicator of the impact of human activities – specifically, greenhouse gas emissions – on our planet. Earth's average temperature has risen more than 2 degrees Fahrenheit (1.2 degrees Celsius) since the late 19th century.”); *and* Intergovernmental Panel on Climate Change (2021) Summary for Policymakers, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), SPM-6 (“The *likely* range of total human-caused global surface temperature increase from 1850–1900 to 2010–2019 [11] is 0.8°C to 1.3°C, with a best estimate of 1.07°C. It is *likely* that well-mixed GHGs contributed a warming of 1.0°C to 2.0°C, other human drivers (principally aerosols) contributed a cooling of 0.0°C to 0.8°C, natural drivers changed global surface temperature by –0.1°C to 0.1°C, and internal variability changed it by –0.2°C to 0.2°C. It is *very likely* that well-mixed GHGs were the main driver[12] of tropospheric warming since 1979, and *extremely likely* that human-caused stratospheric ozone depletion was the main driver of cooling of the lower stratosphere between 1979 and the mid-1990s.”… Footnote 11: “The period distinction with A.1.2 arises because the attribution studies consider this slightly earlier period. The observed warming to 2010–2019 is 1.06 [0.88 to 1.21] °C.” Footnote 12: “Throughout this SPM, ‘main driver’ means responsible for more than 50% of the change.”).

[15] Intergovernmental Panel on Climate Change (2021) Summary for Policymakers, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), SPM-10 (“It is *virtually certain* that hot extremes (including heatwaves) have become more frequent and more intense across most land regions since the 1950s, while cold extremes (including cold waves) have become less frequent and less severe, with *high confidence* that human-induced climate change is the main driver[14] of these changes. Some recent hot extremes observed over the past decade would have been *extremely unlikely* to occur without human influence on the climate system. Marine heatwaves have approximately doubled in frequency since the 1980s (*high confidence*), and human influence has *very likely* contributed to most of them since at least 2006.”). *See also* Kotz M., Wenz L., & Levermann A. (2021) Footprint of greenhouse forcing in daily temperature variability, Proc. Nat’l. Acad. Sci. 118(32): 1–8, 1 (“Assessing historical changes to daily temperature variability in comparison with those from state-of-the-art climate models, we show that variability has changed with distinct global patterns over the past 65 years, changes which are

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attributable to rising concentrations of greenhouse gases. If these rises continue, temperature variability is projected to increase by up to 100% at low latitudes and decrease by 40% at northern high latitudes by the end of the century.”).

[16] Philip S. Y., *et al.* (2021) Rapid attribution analysis of the extraordinary heatwave on the Pacific Coast of the US and Canada, **World Weather Attribution, 20 (“**Results for current vs past climate, i.e. for 1.2°C of global warming vs pre-industrial conditions (1850-1900), indicate an increase in intensity of about 2.0 ˚C (1.2 ˚C to 2.8 ˚C) and a PR of at least 150. Model results for additional future changes if global warming reaches 2°C indicate another increase in intensity of about 1.3 ˚C (0.8 ˚C to 1.7 ˚C) and a PR of at least 3, with a best estimate of 175. This means that an event like the current one, that is currently estimated to occur only once every 1000 years, would occur roughly every 5 to 10 years in that future world with 2°C of global warming.”).

[17] Philip S. Y., *et al.* (2021) Rapid attribution analysis of the extraordinary heatwave on the Pacific Coast of the US and Canada, **World Weather Attribution, 1–37, 1 (“**Also, this heatwave was about 2°C hotter than it would have been if it had occurred at the beginning of the industrial revolution (when global mean temperatures were 1.2°C cooler than today.”). *See also* Newburger E. (1 July 2021) Historic heat wave linked to hundreds of deaths in Pacific Northwest and Canada, CNBC (“Dr. Jennifer Vines, Multnomah County’s health officer, said the preliminary cause of death was hyperthermia, an abnormally high body temperature resulting from an inability of the body to deal with heat. Many of the dead were found alone and without air conditioning…. “While it is too early to say with certainty how many of these deaths are heat related, it is believed likely that the significant increase in deaths reported is attributable to the extreme weather B.C. has experienced,” Lapointe said in a statement.”).

[18] Philip S. Y., *et al.* (2021) Rapid attribution analysis of the extraordinary heatwave on the Pacific Coast of the US and Canada, **World Weather Attribution, 1–37, 1 (“**Looking into the future, in a world with 2°C of global warming (0.8°C warmer than today which at current emission levels would be reached as early as the 2040s), this event would have been another degree hotter. An event like this -- currently estimated to occur only once every 1000 years, would occur roughly every 5 to 10 years in that future world with 2°C of global warming.”).

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

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

[21] Harrington L. J., Ebi K. L., Frame D. J., & Otto F. E. L. (2022) Integrating attribution with adaptation for unprecedented future heatwaves, Clim. Change 172: 1–7, 3 (“Thus, specifically resolving whether a recent heatwave — say, one which occurs once per decade in today’s climate — would have occurred either once in 100 generations or once in 1000 generations in a pre-industrial climate, is no longer useful. When the current climate has changed so significantly that the pre-industrial world becomes a poor basis of comparison, other tools are needed to instead quantify future changes in exposure or the effectiveness of adaptation to changes in extreme weather seen over recent decades.”); *as discussed in* Sengupta S. (3 May 2022) An extraordinary heat wave exposes the limits of protecting people, The New York Times (“For more than a month now, across much of the country (and in next door Pakistan),

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temperatures have soared and stayed there. The capital, Delhi, topped 46 degrees Celsius (114 degrees Fahrenheit) last week. West Bengal, in the muggy east of the country, where my family is from, is among those regions where the combination of heat and humidity could rise to a threshold where the human body is in fact at risk of cooking itself. That theoretical limit is a "wet bulb" temperature — when a thermometer is wrapped in a wet cloth, accounting for both heat and humidity — of 35 degrees Celsius. In neighboring Pakistan, the Meteorological Department warned last week that daily high temperatures were 5 to 8 degrees Celsius above normal, and that in the mountainous north, fast-melting snow and ice could cause glacial lakes to burst. How much of this extreme heat can be blamed on climate change? That's now becoming an "obsolete question," Friederike Otto, a leader in the science of attributing extreme weather events to climate change, said in a paper published Monday. The rise in the average global temperature has already intensified heat waves "many times faster than any other type of extreme weather," the paper concluded. Get used to extremes. Adapt. As much as possible."). *See also* Tunio Z. (7 May 2022) An unprecedented heat wave in India and Pakistan is putting the lives of more than a billion people at risk, Inside Climate News.

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

[23] National Oceanic and Atmospheric Administration National Centers for Environmental Information (2021) State of the Climate: Global Climate Report for May 2021 ("The seven warmest years since 1880 have all occurred since 2014, while the 10 warmest years have occurred since 2005... The decadal global land and ocean surface average temperature anomaly for 2011–2020 was the warmest decade on record for the globe, with a surface global temperature of +0.82°C (+1.48°F) above the 20th century average. This surpassed the previous decadal record (2001–2010) value of +0.62°C (+1.12°F)."). *See also* Intergovernmental Panel on Climate Change (2021) Summary for Policymakers, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), SPM-5 ("Each of the last four decades has been successively warmer than any decade that preceded it since 1850. Global surface temperature in the first two decades of the 21st century (2001-2020) was 0.99 [0.84-1.10] °C higher than 1850-19009. Global surface temperature was 1.09 [0.95 to 1.20] °C higher in 2011–2020 than 1850–1900, with larger increases over land (1.59 [1.34 to 1.83] °C) than over the ocean (0.88 [0.68 to 1.01] °C). The estimated increase in global surface temperature since AR5 is principally due to further warming since 2003–2012 (+0.19 [0.16 to 0.22] °C). Additionally, methodological advances and new datasets contributed approximately 0.1ºC to the updated estimate of warming in AR6[10]."… Footnote 10: "Since AR5, methodological advances and new datasets have provided a more complete spatial representation of changes in surface temperature, including in the Arctic. These and other improvements have additionally increased the estimate of global surface temperature change by approximately 0.1 ºC, but this increase does not represent additional physical warming since the AR5.").

[24] Xu Y., Ramanathan V., & Victor D. G. (2018) Global warming will happen faster than we think, Nature 564(7734): 30–32, 31 ("In 2017, industrial carbon dioxide emissions are estimated to have reached about 37 gigatonnes2. This puts them on track with the highest emissions trajectory the IPCC has modelled so far. This dark news means that the next 25 years are poised to warm at a rate of 0.25–0.32 °C per decade3. That is faster than the 0.2 °C per decade that we have experienced since the 2000s, and which the IPCC used in its special report.").

[25] National Oceanic and Atmospheric Administration (8 June 2021) Despite pandemic shutdowns, carbon dioxide and methane surged in 2020 ("NOAA's preliminary analysis showed the annual increase in atmospheric methane for 2020 was 14.7 parts per billion (ppb), which is the largest annual increase recorded since systematic measurements began in 1983."). *See also* Vaughan A. (7 January 2022) Record levels of greenhouse gas methane are a 'fire alarm moment', New Scientist ("According to data compiled by the US National Oceanic and Atmospheric Administration (NOAA), average atmospheric concentrations of methane reached a record 1900 parts per billion (ppb) in September 2021, the highest in nearly four decades of records. The figure stood at 1638 ppb in 1983."); *and* Pultarova T. (11 January 2022) Satellites reveal record high methane concentrations despite reduction pledges, Space.

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[26] National Oceanic and Atmospheric Administration (2022) Increase in atmospheric methane set another record during 2021 ("NOAA's preliminary analysis showed the annual increase in atmospheric methane during 2021 was 17 parts per billion (ppb), the largest annual increase recorded since systematic measurements began in 1983. The increase during 2020 was 15.3 ppb. Atmospheric methane levels averaged 1,895.7 ppb during 2021, or around 162% greater than pre-industrial levels. From NOAA's observations, scientists estimate global methane emissions in 2021 are 15% higher than the 1984-2006 period.").

[27] National Oceanic and Atmospheric Administration (5 May 2021) Trends in Atmospheric Carbon Dioxide, Global Monitoring Laboratory (*last visited* 9 May 2022) April 2022 monthly CO_2 levels averaged 420.23 ppm. *See also* National Oceanic and Atmospheric Administration (2021) Carbon dioxide peaks near 420 parts per million at Mauna Loa observatory ("Atmospheric carbon dioxide measured at NOAA's Mauna Loa Atmospheric Baseline Observatory peaked for 2021 in May at a monthly average of 419 parts per million (ppm), the highest level since accurate measurements began 63 years ago… The atmospheric burden of CO_2 is now comparable to where it was during the Pliocene Climatic Optimum, between 4.1 and 4.5 million years ago, when CO_2 was close to, or above 400 ppm. During that time, sea level was about 78 feet higher than today, the average temperature was 7 degrees Fahrenheit higher than in pre-industrial times, and studies indicate large forests occupied areas of the Arctic that are now tundra."). *Note* 420 ppm is a 50% increase over pre-industrial levels of 280 ppm.

[28] National Oceanic and Atmospheric Administration Global Monitoring Laboratory (2021) NOAA Global Monitoring Laboratory – The NOAA Annual Greenhouse Gas Index (AGGI) (*last visited* 3 August 2021) ("For example, the atmospheric abundance of CO_2 has increased by an average of 1.85 ppm per year over the past 41 years (1979-2020). This increase in CO_2 is accelerating — while it averaged about 1.6 ppm per year in the 1980s and 1.5 ppm per year in the 1990s, the growth rate increased to 2.4 ppm per year during the last decade (2009-2020). The annual CO_2 increase from 1 Jan 2020 to 1 Jan 2021 was 2.50 ± 0.08 ppm (see https://gml.noaa.gov/ccgg/trends/global.html), which is slightly higher than the average for the previous decade, and much higher than the two decades before that.").

[29] Intergovernmental Panel on Climate Change (2022) Summary for Policymakers, *in* CLIMATE CHANGE 2022: MITIGATION OF CLIMATE CHANGE, *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Shukla P. R., *et al.* (eds.), SPM-31 ("In modelled global low emission pathways, the projected reduction of cooling and warming aerosol emissions over time leads to net warming in the near- to mid-term. In these mitigation pathways, the projected reductions of cooling aerosols are mostly due to reduced fossil fuel combustion that was not equipped with effective air pollution controls."). *See also* Naik V., *et al.* (2021) Chapter 6: Short-lived climate forcers, in CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 6-8 ("Additional CH_4 and BC mitigation would contribute to offsetting the additional warming associated with SO_2 reductions that would accompany decarbonization (*high confidence*)."); Ramanathan V. & Feng Y. (2008) On avoiding dangerous anthropogenic interference with the climate system: Formidable challenges ahead, PROC. NAT'L. ACAD. SCI. 105(38): 14245–14250, 14248 ("Switching from coal to ''cleaner'' natural gas will reduce CO_2 emission and thus would be effective in minimizing future increases in the committed warming. However, because it also reduces air pollution and thus the ABC [Atmospheric Brown Cloud] masking effect, it may speed up the approach to the committed warming of 2.4°C (1.4–4.3°C)."); *and* United Nations Environment Programme & World Meteorological Organization (2011) INTEGRATED ASSESSMENT OF BLACK CARBON AND TROPOSPHERIC OZONE, 254 ("Evaluating global mean temperature change, it was found that the targeted measures to reduce emissions of methane and BC could greatly reduce warming rates over the next few decades (Figure 6.1; Box 6.1). When all measures are fully implemented, warming during the 2030s relative to the present would be only half as much as in the reference scenario. In contrast, even a fairly aggressive strategy to reduce CO_2 emissions, as for the CO_2-measures scenario, does little to mitigate warming until after the next 20-30 years (Box 6.2). In fact, sulphur dioxide (SO_2) is coemitted with CO_2 in some of the most highly emitting activities, coal burning in large-scale combustion such as in power plants, for example, that are obvious targets for reduced usage under a CO_2-emissions mitigation strategy. Hence such strategies can lead to additional near-term warming (Figure 6.1), in a well-known temporary effect (e.g. Raes and Seinfeld, 2009), although most of the nearterm warming is driven by CO_2 emissions in the past. The CO_2-measures scenario clearly leads to long-term benefits however, with a dramatically lower warming rate at 2070 under that scenario than under the scenario with only CH_4 and BC measures (see Figure 6.1 and timescales in Box 6.2).

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

[30] Intergovernmental Panel on Climate Change (2022) Summary for Policymakers, *in* Climate Change 2022: Mitigation of Climate Change, *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Shukla P. R., *et al.* (eds.), SPM-22 ("C.1.2 In modelled pathways that limit warming to 2°C (>67%) assuming immediate action, global net CO_2 emissions are reduced compared to modelled 2019 emissions by 27% [11–46%] in 2030 and by 52% [36-70%] in 2040; and global CH_4 emissions are reduced by 24% [9–53%] in 2030 and by 37% [20–60%] in 2040. In pathways that limit warming to 1.5°C (>50%) with no or limited overshoot global net CO_2 emissions are reduced compared to modelled 2019 emissions by 48% [36–69%] in 2030 and by 80% [61-109%] in 2040; and global CH_4 emissions are reduced by 34% [21–57%] in 2030 and 44% [31-63%] in 2040. There are similar reductions of non-CO_2 emissions by 2050 in both types of pathways: CH_4 is reduced by 45% [25–70%]; N_2O is reduced by 20% [-5 – 55%]; and F-Gases are reduced by 85% [20–90%]. [FOOTNOTE 44] Across most modelled pathways, this is the maximum technical potential for anthropogenic CH_4 reductions in the underlying models (*high confidence*). Further emissions reductions, as illustrated by the IMP-SP pathway, may be achieved through changes in activity levels and/or technological innovations beyond those represented in the majority of the pathways (*medium confidence*). Higher emissions reductions of CH_4 could further reduce peak warming. (*high confidence*) (Figure SPM.5) {3.3}").

[31] Intergovernmental Panel on Climate Change (2022) Summary for Policymakers, *in* Climate Change 2022: Mitigation of Climate Change, *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Shukla P. R., *et al.* (eds.), SPM-30–SPM-31 ("Deep GHG emissions reductions by 2030 and 2040, particularly reductions of methane emissions, lower peak warming, reduce the likelihood of overshooting warming limits and lead to less reliance on net negative CO_2 emissions that reverse warming in the latter half of the century… Future non-CO_2 warming depends on reductions in non-CO_2 GHG, aerosol and their precursor, and ozone precursor emissions. In modelled global low emission pathways, the projected reduction of cooling and warming aerosol emissions over time leads to net warming in the near- to mid-term. In these mitigation pathways, the projected reductions of cooling aerosols are mostly due to reduced fossil fuel combustion that was not equipped with effective air pollution controls. Non-CO_2 GHG emissions at the time of net zero CO_2 are projected to be of similar magnitude in modelled pathways that limit warming to 2°C (>67%) or lower. These non-CO_2 GHG emissions are about 8 [5–11] $GtCO_2$-eq per year, with the largest fraction from CH_4 (60% [55–80%]), followed by N_2O (30% [20–35%]) and F-gases (3% [2–20%]). [FOOTNOTE 52] Due to the short lifetime of CH_4 in the atmosphere, projected deep reduction of CH_4 emissions up until the time of net zero CO_2 in modelled mitigation pathways effectively reduces peak global warming. (*high confidence*) {3.3, AR6 WG I SPM D1.7}").

[32] Intergovernmental Panel on Climate Change (2018) Summary for Policymakers, *in* Global Warming of 1.5 °C, *Special Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), SPM-15, SPM-17 ("In model pathways with no or limited overshoot of 1.5 °C, global net anthropogenic CO_2 emissions decline by about 45% from 2010 levels by 2030 (40–60% interquartile range), reaching net zero around 2050 (2045–2055 interquartile range)…. Modelled pathways that limit global warming to 1.5 °C with no or limited overshoot involve deep reductions in emissions of methane and black carbon (35% or more of both by 2050 relative to 2010)."; "C.3. All pathways that limit global warming to 1.5 °C with limited or no overshoot project the use of carbon dioxide removal (CDR) on the order of 100–1000 $GtCO_2$ over the 21st century.").

[35] Parties to the United Nations Framework Convention on Climate Change (UNFCCC) are required to report emissions on a gas-by-gas basis in units of mass. Framework Convention on Climate Change Dec. 18/CMA.1, FCCC/PA/CMA/2018/3/Add.2, at Annex ¶47 (March 19, 2019) ("47. Each Party shall report estimates of emissions and removals for all categories, gases and carbon pools considered in the GHG inventory throughout the reported period on a gas-by-gas basis in units of mass at the most disaggregated level, in accordance with the IPCC guidelines referred to in paragraph 20 above, using the common reporting tables, including a descriptive summary and figures underlying emission trends, with emissions by sources listed separately from removals by sinks, except in cases where

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it may be technically impossible to separate information on emissions and removals in the LULUCF sector, and noting that a minimum level of aggregation is needed to protect confidential business and military information."). *See also* Allen M. R., *et al.* (2022) *Indicate separate contributions of long-lived and short-lived greenhouse gases in emission targets*, NPJ CLIM. ATMOS. SCI. 5(5): 1–4, 1 ("As researchers who have published over recent years on the issue of comparing the climate effects of different greenhouse gases, we would like to highlight a simple innovation that would enhance the transparency of stocktakes of progress towards achieving any multi-decade-timescale global temperature goal. In addition to specifying targets for total CO_2-equivalent emissions of all greenhouse gases, governments and corporations could also indicate the separate contribution to these totals from greenhouse gases with lifetimes around 100 years or longer, notably CO_2 and nitrous oxide, and the contribution from Short-Lived Climate Forcers (SLCFs), notably methane and some hydrofluorocarbons. This separate indication would support an objective assessment of the implications of aggregated emission targets for global temperature, in alignment with the UNFCCC Parties' Decision (4/CMA.1)1 to provide 'information necessary for clarity, transparency and understanding" in nationally determined contributions (NDCs) and long-term low-emission development strategies (LT-LEDSs).'").

[36] Abernethy S. & Jackson R. B. (2022) *Global temperature goals should determine the time horizons for greenhouse gas emission metrics*, ENVIRON. RES. LETT. 17(2): 024019 ("Although NDCs and long-term national pledges are currently insufficient to keep warming below 2 °C, let alone 1.5 °C [50–52], the time horizons used for emission metrics should nevertheless be consistent with that central goal of the Paris Agreement. We therefore support the use of the 20 year time horizon over the 100 year version, when binary choices between these two must be made, due to the better alignment of the former with the temperature goals of the Paris Agreement. The 50 year time horizon, not yet in widespread use but now included in IPCC AR6, is in fact the only time horizon that the IPCC presents that falls within the range of time horizons that align with the Paris Agreement temperature goals (24–58 years). However, to best align emission metrics with the Paris Agreement 1.5 ° C goal, we recommend the use of the 24 year time horizon, using 2045 as the end point time, with its associated $GWP_{1.5°C} = 75$ and $GTP_{1.5\,°C} = 41$."). *As discussed in* McKenna P. (9 February 2022) *To Counter Global Warming, Focus Far More on Methane, a New Study Recommends*, INSIDE CLIMATE NEWS ("The Environmental Protection Agency is drastically undervaluing the potency of methane as a greenhouse gas when the agency compares methane's climate impact to that of carbon dioxide, a new study concludes. The EPA's climate accounting for methane is "arbitrary and unjustified" and three times too low to meet the goals set in the Paris climate agreement, the research report, published Wednesday in the journal Environmental Research Letters, found."); *and* Rathi A. (15 February 2022) *The Case Against Methane Emissions Keeps Getting Stronger*, BLOOMBERG.

[37] Parties to the United Nations Framework Convention on Climate Change (UNFCCC) are required to report emissions on a gas-by-gas basis in units of mass. Framework Convention on Climate Change Dec. 18/CMA.1, FCCC/PA/CMA/2018/3/Add.2, at Annex ¶ 37 (March 19, 2019) ("37. Each Party shall use the 100-year time-horizon global warming potential (GWP) values from the IPCC Fifth Assessment Report, or 100-year time-horizon GWP values from a subsequent IPCC assessment report as agreed upon by the CMA, to report aggregate emissions and removals of GHGs, expressed in CO_2 eq. Each Party may in addition also use other metrics (e.g., global temperature potential) to report supplemental information on aggregate emissions and removals of GHGs, expressed in CO_2 eq. In such cases, the Party shall provide in the national inventory document information on the values of the metrics used and the IPCC assessment report they were sourced from.").

[38] Smith C., Nicholls Z. R. J., Armour K. C., Collins W., Forster P., Meinshausen M., Palmer M. D., & Watanabe M. (2021) *Chapter 7 Supplementary Materials: The Earth's energy budget, climate feedbacks, and climate sensitivity*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), Table 7.SM.7.

[39] Lynch J., Cain M., Pierrehumbert R., & Allen M. (2020) *Demonstrating GWP*: a means of reporting warming-equivalent emissions that captures the contrasting impacts of short- and long-lived climate pollutants*, ENVIRON. RES. LETT. 15(4): 044023 ("Following these behaviours, sustained emissions of an SLCP therefore result in a similar impact to a one-off release of a fixed amount of CO_2: both lead to a relatively stable long-term increase in radiative forcing. Thus an alternative means of equivalence can be derived, relating a change in the rate of emissions of SLCPs to a fixed quantity of CO_2…").

[40] Cain M., Lynch J., Allen M. R., Fuglestvedt J. S., Frame D. J., & Macey A. H. (2019) *Improved calculation of warming-equivalent emissions for short-lived climate pollutants*, NPJ CLIM. ATMOS. SCI. 2(29): 1–7, 1 ("We have

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used an empirical method to find a definition of GWP* that preserves the link between an emission and the warming it generates in the medium term up to 2100. The physical interpretation of equation 1 is that the flow term (with coefficient *r*) represents the fast climate response to a change in radiative forcing, generated by the atmospheric and ocean mixed-layer response.30 The timescale of this response is about 4 years here.31 The stock term (with coefficient *s*) represents the slower timescale climate response to a change in radiative forcing, due to the deep ocean response. This effect means that the climate responds slowly to past changes in radiative forcing, and is why the climate is currently far from equilibrium. We have approximated this response by treating a quarter of the climate response to a SLCP as "cumulative".").

[41] Rogelj J. & Schleussner C.-F. (2021) *Reply to Comment on `Unintentional unfairness when applying new greenhouse gas emissions metrics at country level'*, Environ. Res. Lett. 16(6): 068002 ("These ethical issues arise from moving away from an emissions centered metric like GWP-100—where every unit of emissions of a certain GHG is treated equally and independent of the emitter or timing of emissions—to metrics like GWP*—which focus on additional warming and where the treatment of a unit of emissions depends on the emitter and their emission history… Meanwhile, a group of the world's biggest diary producers seems happy to consider the grandfathering GWP* perspective and explicitly dismisses other fairness perspectives that would increase their companies' responsibility for reducing methane emissions (Cady 2020)."); *citing* Cady R. (2020) *A Literature Review of GWP*: A proposed method for estimating global warming potential (GWP*) of short-lived climate pollutants like methane*, The Global Dairy Platform; *as discussed in* Elgin B. (19 Oct 2021) *Beef Industry Tries to Erase Its Emissions With Fuzzy Methane Math*. Bloomberg Green.

[42] 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*, Comment, Nature 575(7784): 592–595, 593 ("A further key impetus to limit warming to 1.5 °C is that other tipping points could be triggered at low levels of global warming. The latest IPCC models projected a cluster of abrupt shifts between 1.5 °C and 2 °C, several of which involve sea ice. This ice is already shrinking rapidly in the Arctic…."); Arias P. A., *et al.* (2021) *Technical Summary*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), TS-71–TS-72 ("It is *likely* that under stabilization of global warming at 1.5°C, 2.0°C, or 3.0°C relative to 1850–1900, the AMOC will continue to weaken for several decades by about 15%, 20% and 30% of its strength and then recover to pre-decline values over several centuries (*medium confidence*). At sustained warming levels between 2°C and 3°C, there is limited evidence that the Greenland and West Antarctic Ice Sheets will be lost almost completely and irreversibly over multiple millennia; both the probability of their complete loss and the rate of mass loss increases with higher surface temperatures (*high confidence*). At sustained warming levels between 3°C and 5°C, near-complete loss of the Greenland Ice Sheet and complete loss of the West Antarctic Ice Sheet is projected to occur irreversibly over multiple millennia (*medium confidence*); with substantial parts or all of Wilkes Subglacial Basin in East Antarctica lost over multiple millennia (*low confidence*). Early-warning signals of accelerated sea-level-rise from Antarctica, could possibly be observed within the next few decades. For other hazards (e.g., ice sheet behaviour, glacier mass loss and global mean sea level change, coastal floods, coastal erosion, air pollution, and ocean acidification) the time and/or scenario dimensions remain critical, and a simple and robust relationship with global warming level cannot be established (*high confidence*)… The response of biogeochemical cycles to anthropogenic perturbations can be abrupt at regional scales and irreversible on decadal to century time scales (*high confidence*). The probability of crossing uncertain regional thresholds increases with climate change (*high confidence*). It is *very unlikely* that gas clathrates (mostly methane) in deeper terrestrial permafrost and subsea clathrates will lead to a detectable departure from the emissions trajectory during this century. Possible abrupt changes and tipping points in biogeochemical cycles lead to additional uncertainty in 21st century atmospheric GHG concentrations, but future anthropogenic emissions remain the dominant uncertainty (*high confidence*). There is potential for abrupt water cycle changes in some high-emission scenarios, but there is no

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overall consistency regarding the magnitude and timing of such changes. Positive land surface feedbacks, including vegetation, dust, and snow, can contribute to abrupt changes in aridity, but there is only low confidence that such changes will occur during the 21st century. Continued Amazon deforestation, combined with a warming climate, raises the probability that this ecosystem will cross a tipping point into a dry state during the 21st century (*low confidence*). {TS3.2.2, 5.4.3, 5.4.5, 5.4.8, 5.4.9, 8.6.2, 8.6.3, Cross-chapter Box 12.1}"); *and* Lee J. Y., *et al.* (2021) *Chapter 4: Future Global Climate: Scenario-Based Projections and Near-Term Information*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 4-96 (Table 4.1 lists 15 components of the Earth system susceptible to tipping points).

[43] Lenton T. M., Rockstrom J., Gaffney O., Rahmstorf S., Richardson K., Steffen W., & Schellnhuber H. J. (2019) *Climate tipping points—too risky to bet against*, Comment, Nature 575(7784): 592–595, 594 ("In our view, the clearest emergency would be if we were approaching a global cascade of tipping points that led to a new, less habitable, 'hothouse' climate state[11]. Interactions could happen through ocean and atmospheric circulation or through feedbacks that increase greenhouse-gas levels and global temperature."). *See also* Wunderling N., Donges J. F., Kurths J., & Winkelmann R. (2021) *Interacting tipping elements increase risk of climate domino effects under global warming*, Earth Syst. Dyn. 12(2): 601–619, 614 ("In this study, we show that this risk increases significantly when considering interactions between these climate tipping elements and that these interactions tend to have an overall destabilising effect. Altogether, with the exception of the Greenland Ice Sheet, interactions effectively push the critical threshold temperatures to lower warming levels, thereby reducing the overall stability of the climate system. The domino-like interactions also foster cascading, non-linear responses. Under these circumstances, our model indicates that cascades are predominantly initiated by the polar ice sheets and mediated by the AMOC. Therefore, our results also imply that the negative feedback loop connecting the Greenland Ice Sheet and the AMOC might not be able to stabilise the climate system as a whole."); *and* Rocha J. C., Peterson G., Bodin Ö., & Levin S. (2018) *Cascading regime shifts within and across scales*, Science 362(6421): 1379–1383, 1383 ("A key lesson from our study is that regime shifts can be interconnected. Regime shifts should not be studied in isolation under the assumption that they are independent systems. Methods and data collection need to be further developed to account for the possibility of cascading effects. Our finding that ~45% of regime shift couplings can have structural dependence suggests that current approaches to environmental management and governance underestimate the likelihood of cascading effects.").

[44] Drijfhout S., Bathiany S., Beaulieu C., Brovkin V., Claussen M., Huntingford C., Scheffer M., Sgubin G., & Swingedouw D. (2015) *Catalogue of abrupt shifts in Intergovernmental Panel on Climate Change climate models*, Proc. Nat'l. Acad. Sci. 112(43): E5777–E5786, E5784 ("Permafrost carbon release (51) and methane hydrates release (52) were not expected in CMIP5 simulations, because of missing biogeochemical components in those models capable of simulating such changes."). *See also* Bathiany S., Hidding J., & Scheffer M. (2020) *Edge Detection Reveals Abrupt and Extreme Climate Events*, J. Clim. 33(15): 6399–6421, 6416 ("Despite their societal relevance, our knowledge about the risks of future abrupt climate shifts is far from robust. Several important aspects are highly uncertain: future greenhouse gas emissions (scenario uncertainty), the current climate state (initial condition uncertainty), the questionwhether and how to model specific processes (structural uncertainty), and what values one should choose for parameters appearing in the equations (parametric uncertainty). Such uncertainties can be explored using ensemble simulations. For example, by running many simulations with different combinations of parameter values a perturbed-physics ensemble can address how parameter uncertainty affects the occurrence of extreme events (Clark et al. 2006). This strategy can be particularly beneficial for studying abrupt events as well since abrupt shifts are associated with region-specific processes, whereas models are usually calibrated to produce a realistic global mean climate at the expense of regional realism (Mauritsen et al. 2012; McNeall et al. 2016). The currently available model configurations are therefore neither reliable nor sufficient to assess the risk of abrupt shifts (Drijfhout et al. 2015). It is hence very plausible that yet-undiscovered tipping points can occur in climate models."); *and* Canadell J. G., *et al.* (2021) *Chapter 5: Global Carbon and other Biogeochemical Cycles and Feedbacks*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 5-78 ("There is *low confidence* in the estimate of the non-CO_2 biogeochemical feedbacks, due to the large range in the estimates of α for some individual feedbacks (Figure 5.29c), which can be attributed to the diversity in how models account for these feedbacks, limited process-level understanding, and the existence of known feedbacks for which there is not sufficient evidence to assess the feedback strength.").

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[45] Lenton T. M., Rockstrom J., Gaffney O., Rahmstorf S., Richardson K., Steffen W., & Schellnhuber H. J. (2019) *Climate tipping points—too risky to bet against*, Comment, NATURE, 575(7784): 592–595, 594 ("In our view, the clearest emergency would be if we were approaching a global cascade of tipping points that led to a new, less habitable, 'hothouse' climate state11. Interactions could happen through ocean and atmospheric circulation or through feedbacks that increase greenhouse-gas levels and global temperature. Alternatively, strong cloud feedbacks could cause a global tipping point12,13.We argue that cascading effects might be common. Research last year14 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 interactions14. In our view, examples are starting to be observed. … If damaging tipping cascades can occur and a global tipping point cannot be ruled out, then this is an existential threat to civilization. No amount of economic cost–benefit analysis is going to help us. We need to change our approach to the climate problem. … In our view, the evidence from tipping points alone suggests that we are in a state of planetary emergency: both the risk and urgency of the situation are acute….").

[46] Intergovernmental Panel on Climate Change (2022) *Summary for Policymakers*, *in* CLIMATE CHANGE 2022: IMPACTS, ADAPTATION, AND VULNERABILITY, *Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Pörtner H.-O., *et al.* (eds.), SPM-20 ("SPM.B.6 If global warming transiently exceeds 1.5°C in the coming decades or later (overshoot)[37], then many human and natural systems will face additional severe risks, compared to remaining below 1.5°C (*high confidence*). Depending on the magnitude and duration of overshoot, some impacts will cause release of additional greenhouse gases (*medium confidence*) and some will be irreversible, even if global warming is reduced (*high confidence*). (Figure SPM.3) {2.5, 3.4, 12.3, 16.6, CCB SLR, CCB DEEP, Box SPM.1} SPM.B.6.1 While model-based assessments of the impacts of overshoot pathways are limited, observations and current understanding of processes permit assessment of impacts from overshoot. Additional warming, e.g., above 1.5°C during an overshoot period this century, will result in irreversible impacts on certain ecosystems with low resilience, such as polar, mountain, and coastal ecosystems, impacted by ice-sheet, glacier melt, or by accelerating and higher committed sea level rise (*high confidence*).[38] Risks to human systems will increase, including those to infrastructure, low-lying coastal settlements, some ecosystem-based adaptation measures, and associated livelihoods (*high confidence*), cultural and spiritual values (*medium confidence*). Projected impacts are less severe with shorter duration and lower levels of overshoot (*medium confidence*). {2.5, 3.4, 12.3, 13.2, 16.5, 16.6, CCP 1.2, CCP5.3, CCP6.1, CCP6.2, CCP2.2, CCB SLR, Box TS4, SROCC 2.3, SROCC 5.4, WG1 SPM B5 and C3} SPM.B.6.2 Risk of severe impacts increase with every additional increment of global warming during overshoot (*high confidence*). In high-carbon ecosystems (currently storing 3,000 to 4,000 GtC)[39] such impacts are already observed and are projected to increase with every additional increment of global warming, such as increased wildfires, mass mortality of trees, drying of peatlands, and thawing of permafrost, weakening natural land carbon sinks and increasing releases of greenhouse gases (*medium confidence*). The resulting contribution to a potential amplification of global warming indicates that a return to a given global warming level or below would be more challenging (*medium confidence*). {2.4, 2.5, CCP4.2, WG1 SPM B.4.3, SROCC 5.4}").

[47] 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*, Comment, NATURE 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."); 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."); *and* Fox-Kemper B., *et al.*

(2021) *Chapter 9: Ocean, Cryosphere and Sea Level Change*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 9-48 ("The SR1.5 assessed with *high confidence* that there is no hysteresis in the loss of Arctic summer sea ice. In addition, there is no tipping point or critical threshold in global mean temperature beyond which the loss of summer sea ice becomes self-accelerating and irreversible (*high confidence*).").

[48] Jacobs P., Lenssen N. J. L., Schmidt G. A., & Rohde R. A. (2021) *The Arctic Is Now Warming Four Times As Fast As the Rest of the Globe*, Presentation at the American Geophysical Union Fall Meeting, A13E-02 ("We demonstrate the Arctic is likely warming over 4 times faster than the rest of the world, some 3-4 times the global average, with higher rates found both for more recent intervals as well as more accurate latitudinal boundaries. These results stand in contrast to the widely-held conventional wisdom — prevalent across scientific and lay publications alike — that the Arctic is "only" warming around twice as fast as the global mean."); *discussed in* Voosen P. (14 December 2021) *The Arctic is warming four times faster than the rest of the world*, Science.

[49] Druckenmiller M. L., *et al.* (2021) *The Arctic*, Bull. Am. Met. Soc. 102(8): S263–S316, S280 ("September is the month when the minimum annual sea ice extent occurs. In 2020, this average monthly ice extent was 3.92 million km^2 (Fig. 5.8b), the second lowest monthly extent in the 42-year satellite record. On 15 September, the annual minimum Arctic sea ice extent of 3.74 million km^2 was reached; this was also the second lowest on record. The September monthly extent has been decreasing at an average rate of −82,700 km^2 per year since 1979 (−13.1% per decade relative to the 1981–2010 average; Fig. 5.8c)."). *See also* 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)."); *and* 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.").

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

[51] 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.").

[52] Intergovernmental Panel on Climate Change (2021) *Summary for Policymakers*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), SPM-14 ("Heating of the climate system has caused global mean sea level rise through ice loss on land and thermal expansion from ocean warming. Thermal expansion explained 50% of sea level rise during 1971– 2018, while ice loss from glaciers contributed 22%, ice sheets 20% and changes in land water storage 8%. The rate of ice sheet loss increased by a factor of four between 1992–1999 and

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2010–2019. Together, ice sheet and glacier mass loss were the dominant contributors to global mean sea level rise during 2006-2018. (*high confidence*).").

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

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

[55] Druckenmiller M. L., *et al.* (2021) *The Arctic*, BULL. AM. MET. SOC. 102(8): S263–S316, S282 ("The dominant ice type is now first-year ice (0–1 years old), which comprised about 70% of the March 2020 Arctic Ocean ice cover. The median ice age dropped from 2–3 years old in the mid-1980s to less than 1 year old by 2020. The total extent of the oldest ice (>4 years old) declined from 2.50 million km^2 in March 1985 to 0.34 million km^2 in March 2020.").

[56] 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 '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.").

[57] Dobricic S., Russo S., Pozzoli L., Wilson J., & Vignati E. (2020) *Increasing occurrence of heat waves in the terrestrial Arctic*, ENVIRON. RES. LETT. 15(2): 024022 ("The increase is mainly over the Canadian Arctic Archipelago and Greenland that are surrounded by ocean undergoing a sea-ice melting trend, while the Eurasian Arctic shows no significant change in heat wave occurrence. Since 2002 the probability of experiencing heat waves in the Arctic has been similar or even higher than in the middle and low latitudes and heat waves have already started to increasingly threaten local vegetation, ecology, human health and economy.").

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

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(2021–40), +3.3°, +4.0°, and +5.1°C in the midterm (2014–60), and +3.5°, +5.8°, and +10.4°C in the long-term (2081–2100) relative to the reference period based on the CMIP6 MMEM.”).

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

[60] National Snow and Ice Data Center (22 September 2021) *Arctic Sea Ice at Highest Minimum Since 2014* (“On September 16, Arctic sea ice likely reached its annual minimum extent of 4.72 million square kilometers (1.82 million square miles). The 2021 minimum is the twelfth lowest in the nearly 43-year satellite record. The last 15 years are the lowest 15 sea ice extents in the satellite record. The amount of multi-year ice (ice that has survived at least one summer melt season), is one of the lowest levels in the ice age record, which began in 1984.”). *See also* National Snow and Ice Data Center (21 September 2020) *Arctic sea ice decline stalls out at second lowest minimum* (“On September 15, Arctic sea ice likely reached its annual minimum extent of 3.74 million square kilometers (1.44 million square miles). The minimum ice extent is the second lowest in the 42-year-old satellite record, reinforcing the long-term downward trend in Arctic ice extent. Sea ice extent will now begin its seasonal increase through autumn and winter. …*Please note that this is a preliminary announcement. Changing winds or late-season melt could still reduce the Arctic ice extent, as happened in 2005 and 2010. NSIDC scientists will release a full analysis of the Arctic melt season, and discuss the Antarctic winter sea ice growth, in early October*. … The 14 lowest extents in the satellite era have all occurred in the last 14 years.”); *and* Richter-Menge J., Druckenmiller M. L. & Thoman R. L. (2020) *15 Years of Arctic Observation: A Retrospective*, *in* Arctic Report Card 2020, Thoman R. L., Richter-Menge J., & Druckenmiller M. L. (eds.), National Oceanic and Atmospheric Administration, 8 (“As it turns out, the first publication in 2006 coincided with a cusp of transformation in the sea ice cover, which is literally and figuratively central to the Arctic system. The 2007 September minimum sea ice extent stunned scientists and grabbed world-wide media attention with a new record minimum that was 23% below the previous record low set in 2005. Just five years later, in 2012, the 2007 record was overtaken by a September minimum sea ice extent that was 18% below 2007. The 2012 record low still stands as of 2020. However, in the 14 years since ARC2006 the late summer sea ice minimum extent has never returned to pre-2007 values.”).

[61] Schweiger A. J., Steele M., Zhang J., Moore G. W. K., & Laidre K. L. (2021) *Accelerated sea ice loss in the Wandel Sea points to a change in the Arctic’s Last Ice Area*, Commun. Earth & Environ. 2: 1–11, 2, 6 (“The Polarstern’s route was guided by satellite images showing extensive areas of open water and sea ice concentration (SIC) as low as 70% at 87N (Figs. 1a, S1b). We define our WS study area by 81.5°N–85°N, 10°W–50°W, the same area where we saw signs of change in February 201810. Daily 2020 WS SIC drops below the 5th percentile of the 1979–2020 time series on July 25 and stays there almost until the end of August (Fig. 1b). August 14, 2020 constitutes a record low 52% SIC minimum (Fig. 1c). Several earlier years (e.g., 1985: 57%, 1990: 67%, and 1991: 62%) also show significant low SIC minima, although none as low as 2020.”); 1 (“During spring 2020, ice accumulated in the WS (Fig. 4a, b) in response to anomalous advection (mostly in February; Fig. 4c, d). As a result, ice thickness was near its 1979–2020 mean value by June 1 according to PIOMAS; Fig. 2c), and actually thicker than in recent years (2011–2019) as confirmed by the combined CryoSat-2/SMOS satellite product… While primarily driven by unusual weather, climate change in the form of thinning sea ice contributed significantly to the record low August 2020 SIC in the WS. Several

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advection events, some relatively early in the melt season, transported sea ice out of the region and allowed the accumulation of heat from the absorption of solar radiation in the ocean. This heat was mixed upward and contributed to rapid melt during high wind events, notably between August 9 and 16. Ocean-forced melting in this area that is traditionally covered by thick, compact ice is a key finding of this study."; "These ensemble experiments underline the importance of both spring sea ice and summer atmospheric forcing to August SIC. In summary, we find that: Spring ice conditions were mostly responsible for the summer SIC anomaly through the end of July, while the atmosphere was mainly responsible for driving SIC to a record low during August. Partitioning the impact of 2020 spring initial sea ice conditions vs. summer atmospheric forcing on the sea ice anomaly at the time of the WS sea ice minimum on August 14 (see "Methods") attributes ~20% to the initial conditions while ~80% is the due to the atmospheric forcing.").

[62] Labe Z., Magnusdottir G., & Stern H. (2018) *Variability of Arctic Sea Ice Thickness Using PIOMAS and the CESM Large Ensemble,* J. Clim. 31(8): 3233–3247, 3245 (Figure 10. "While twenty-first-century sea ice thins substantially in all seasons, a large sea ice cover continues to reform during the cold season. A region of perennially thick ice north of Greenland also remains…..An area of perennially thick sea ice remains north of Greenland during all months of the year, but it significantly thins (especially in September) by the mid-twenty-first century. Average September SIT in all regions eventually falls below 0.5 m during the 21st century.").

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

[64] U.S. Environmental Protection Agency (2015) U.S. National Black Carbon and Methane Emissions: A Report to the Arctic Council, 2, 9 (Figure 1 shows BC emissions north of the 40th parallel in 2011 amounting to 0.51 million metric tons, with 39% from open biomass burning, and 51% of that number [19.89% or ~0.10 MMT] due to wildfires; "In 2011, 51 percent of black carbon emissions from open biomass burning were from wildfires, 43 percent from prescribed burning, with the remainder from agricultural field burning."). *See also* Kim J.-S., Kug J.-S., Jeong S.-J., Park H., & Schaepman-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* Environmental Protection Agency (2012) *Report to Congress on Black Carbon*, EPA-450/R-12-001.

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

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boreal regions of Siberia are not uncommon[7], 2020's fires are unusual in that more than 50% of the detected fires above 65° N occurred on permafrost with high ice content. Ice-rich permafrost is considered to contain the most carbon-rich soils in the Arctic[8] and burning can accelerate thaw and carbon emission rates[9]").

[66] Copernicus Atmosphere Monitoring Service (6 December 2021) *Wildfires wreaked havoc in 2021, CAMS tracked their impact* ("According to the CAMS scientists, global wildfires in 2021 caused an estimated total of 1760 megatonnes of carbon emissions, which is the equivalent of 6450 megatonnes of CO_2. To put this figure into some perspective – total CO_2 emissions from fossil fuel in the EU in 2020 amounted to 2600 megatonnes, in other words - wildfires this year generated 148% more than total EU fossil fuel emissions in 2020."); *discussed in* Ainger J. (7 December 2021) *Wildfires in 2021 Spewed CO_2 Equal to Half of EU's Annual Emissions*, Bloomberg Green. *See also* Copernicus Atmosphere Monitoring Service, *Global fire monitoring* (*last visited* 21 January 2022).

[67] Docquier D. & Koenigk T. (2021) *Observation-based selection of climate models projects Arctic ice-free summers around 2035*, Commun. Earth & Environ. 2: 1–8, 4, 6 ("In the high-emission scenario, five out of six selection criteria that include ocean heat transport provide a first ice-free Arctic in September before 2040 (range of multi-model means: 2032–2039), more than 20 years before the date of ice-free Arctic for the multi-model mean without model selection (i.e. 2061)"; "This model selection reveals that sea-ice area and volume reach lower values at the end of this century compared to the multi-model mean without selection. This arises both from a more rapid reduction in these quantities through this century and from a lower present-day sea-ice area. Using such a model selection, the timing of an almost ice-free Arctic in summer is advanced by up to 29 years in the high-emission scenario, i.e. it could occur as early as around 2035."). *See also* Peng G., Matthews J. L., Wang M., Vose R., & Sun L. (2020) *What Do Global Climate Models Tell Us about Future Arctic Sea Ice Coverage Changes?*, Climate 8: 15 ("Excluding the values later than 2100, the averaged projected [first ice-free Arctic summer year (FIASY)] value for RCP4.5 was 2054 with a spread of 74 years; for RCP8.5, the averaged FIASY was 2042 with a spread of 42 years. ...which put the mean FIASY at 2037. The RCP8.5 projections tended to push FIASY earlier, except for those of the MICRO-ESM and MICRO-ESM-CHEM models. Those two models also tended to project earlier Arctic ice-free dates and longer durations."); Overland J. E. & Wang M. (2013) *When will the summer Arctic be nearly sea ice free?*, Geophys. Res. Lett. 40(10): 2097–2101, 2097 ("Three recent approaches to predictions in the scientific literature are as follows: (1) extrapolation of sea ice volume data, (2) assuming several more rapid loss events such as 2007 and 2012, and (3) climate model projections. Time horizons for a nearly sea ice-free summer for these three approaches are roughly 2020 or earlier, 2030 ± 10 years, and 2040 or later. Loss estimates from models are based on a subset of the most rapid ensemble members. … Observations and citations support the conclusion that most global climate model results in the CMIP5 archive are too conservative in their sea ice projections. Recent data and expert opinion should be considered in addition to model results to advance the very likely timing for future sea ice loss to the first half of the 21st century, with a possibility of major loss within a decade or two."); Guarino M.-V., *et al.* (2020) *Sea-ice-free Arctic during the Last Interglacial supports fast future loss*, Nat. Clim. Change 10: 928–932, 931 ("The predicted year of disappearance of September sea ice under high-emissions scenarios is 2086 for HadCM3 (CMIP3/5), 2048 for HadGEM2-ES (CMIP5) and 2035 for HadGEM3 (CMIP6) (Fig. 4). More broadly, multimodel CMIP3–6 mean predictions (and ranges) for a summer sea-ice-free Arctic are as follows: CMIP3, 2062 (2040–2086); CMIP5, 2048 (2020–2081); and CMIP6, 2046 (2029–2066) (Fig. 4 and Supplementary Table 3). We note that the latest year of sea-ice disappearance for CMIP6 models is 2066 and that 50% of the models predict sea-ice-free conditions between ~2030 and 2040. From this we can see that HadGEM3 is not a particular outlier, in terms of its ECS or projected ice-free year."); *and* Intergovernmental Panel on Climate Change (2021) *Summary for Policymakers*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), Figure SPM.8-b.

[68] Labe Z., Magnusdottir G., & Stern H. (2018) *Variability of Arctic Sea Ice Thickness Using PIOMAS and the CESM Large Ensemble*, J. Clim. 31(8): 3233–3247, 3244 (Figure 11 shows that the timing of the first September sea ice thickness to fall below 0.5 m occurs for all regions as early as 2025, with the exception of Greenland); 3255 ("We also show that the timing of the first September SIT below 0.5 m occurs substantially earlier than the timing of that event for the ensemble mean in the outer marginal seas, but year-to-year variability remains. Recent summer sea ice conditions have already shown this to be the case, for instance, in the Barents–Kara Seas. Even in the area of climatologically thick sea ice north of Greenland, the first September with SIT less than 0.5 m is reached, on average, by 2059 ± 7 years. While future rates of declining SIT may temporarily slow or even pause as a result of this high internal variability and the resiliency of SIV (Tilling et al. 2015; Blanchard-Wrigglesworth and Bitz 2014), future

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simulations from LENS indicate a continued loss of thicker, multiyear sea ice and a reduction in interannual variability.”).

[69] Mallett R. D. C., Stroeve J. C., Tsamados M., Landy J. C., Willatt R., Nandan V., & Liston G. E. (2021) *Faster decline and higher variability in the sea ice thickness of the marginal Arctic seas when accounting for dynamic snow cover*, The Cryosphere 15(5): 2429–2450, 2429, 2441 (“When the sea ice thickness in the period 2002–2018 is calculated using new snow data with more realistic variability and trends, we find mean sea ice thickness in four of the seven marginal seas to be declining between 60 %–100 % faster than when calculated with the conventional climatology.”).

[70] 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.”).

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

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

[73] Pistone K., Eisenman I., & Ramanathan V. (2019) *Radiative Heating of an Ice-Free Arctic Ocean*, Geophys. Res. Lett. 46(13): 7474–7480, 7479 (“The estimate of one trillion tons of CO_2 emissions is computed using the following approximate formula: $f = (5.35\ \mathrm{W/m^2})\ \ln[x/R]$ (Myhre et al., 1998). Here f is the radiative forcing relative to an arbitrary reference value R, x is the atmospheric CO_2 concentration, and ln indicates the natural logarithm. Note that this formula is an expression of the relationship that a doubling of atmospheric CO_2 causes a radiative forcing of 3.71 $\mathrm{W/m^2}$. Considering a radiative forcing of 0.71 $\mathrm{W/m^2}$, this translates to an increase in the atmospheric CO_2 concentration from 400 to 456.7 ppm. Since 1 ppm of atmospheric CO_2 is equivalent to 7.77 Gt (Le Quéré et al., 2018), this increase of

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56.7 ppm weighs 441 Gt. The mean airborne fraction of CO_2 (i.e., fraction of CO_2 emissions that remain in the atmosphere) is estimated to be 0.44 ± 0.06 (section 6.3.2.4 of Ciais et al., 2013). This implies that the emissions needed to increase atmospheric CO_2 enough to cause 0.71 W/m^2 of radiative forcing is 1.0 trillion tons (i.e., 441 Gt/0.44).").

[74] National Oceanic and Atmospheric Administration (2021) *Carbon dioxide peaks near 420 parts per million at Mauna Loa observatory* ("Atmospheric carbon dioxide measured at NOAA's Mauna Loa Atmospheric Baseline Observatory peaked for 2021 in May at a monthly average of 419 parts per million (ppm), the highest level since accurate measurements began 63 years ago… The atmospheric burden of CO_2 is now comparable to where it was during the Pliocene Climatic Optimum, between 4.1 and 4.5 million years ago, when CO_2 was close to, or above 400 ppm. During that time, sea level was about 78 feet higher than today, the average temperature was 7 degrees Fahrenheit higher than in pre-industrial times, and studies indicate large forests occupied areas of the Arctic that are now tundra."). *Note* 420 ppm is a 50% increase over pre-industrial levels of 280 ppm.

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

[76] Forster P., *et al.* (2021) *Chapter 7: The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 7-49 (Table 7.8 gives Effective Radiative Forcings (ERF) for CO_2 of 2.16 (1.90 to 2.41)). *See also* NOAA Earth System Research Laboratory, *The NOAA Annual Greenhouse Gas Index (AGGI)* (*last updated* Spring 2021) (National Oceanic and Atmospheric Administration (NOAA) calculated that the radiative forcing from CO_2 was 2.044 W/m^2 in 2018 and 2.076 W/m^2 in 2019 and 2.111 W/m^2 in 2020).

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

[78] Perovich D., *et al.* (2020) *Sea Ice*, *in* ARCTIC REPORT CARD 2020, Thoman R. L., Richter-Menge J., & Druckenmiller M. L. (eds.), National Oceanic and Atmospheric Administration, 29–30, 48 ("The oldest ice (>4 years old), which once dominated within the Arctic Ocean, now makes up just a small fraction of the Arctic Ocean ice pack in March, when the sea ice cover is at its maximum extent (Fig. 3). In 1985, 33% of the ice pack was very old ice (>4 years), but by March 2019 old ice only constituted 1.2% of the ice pack within the Arctic Ocean. The total extent of the oldest ice declined from 2.52 million km^2 in March 1985 to 0.09 million km^2 in March 2019. … First-year ice now dominates the sea ice cover, comprising ~70% of the March 2019 ice pack, compared to approximately 35–50% in the 1980s.

Given that older ice tends to be thicker, the sea ice cover has transformed from a strong, thick ice mass in the 1980s to a younger, more fragile, and thinner ice mass in recent years. First-year ice is therefore more vulnerable to melting out in summer, thereby increasing the likelihood of lower minimum ice extents."; "The oldest ice (> 4 years old) was once a major component of the Arctic sea ice cover, but now makes up just a small fraction of the March Arctic Ocean ice pack (Fig. 3). In 1985, 33% of the ice pack was very old ice (> 4 years), but by March 2020 old ice only constituted 4.4% of the ice pack within the Arctic Ocean. The total extent of the oldest ice declined from 2.70 million km^2 in March 1985 to 0.34 million km^2 in March 2020. The March 2020 extent of > 4 year old ice increased from the record-low year in 2019 when it was only 1.2% (0.09 million km^2) of the ice cover. This increase was due to 3–4 year old ice surviving a year and aging into > 4 year old ice. The 3–4 year old cover dropped from 6.4% in 2019 to 3.7% in 2020. Overall the percentage of ice 3 years and older was effectively unchanged. Note that these percentages are relative to ice in the Arctic Ocean region (Fig. 3, bottom inset); areas in the peripheral seas outside of this region have little or no older ice and thus do not show any change over time."). *See also* Druckenmiller M. L., *et al.* (2021) *The Arctic*, Bull. Am. Met. Soc. 102(8): S263–S316, S282 ("The dominant ice type is now first-year ice (0–1 years old), which comprised about 70% of the March 2020 Arctic Ocean ice cover. The median ice age dropped from 2–3 years old in the mid-1980s to less than 1 year old by 2020. The total extent of the oldest ice (>4 years old) declined from 2.50 million km^2 in March 1985 to 0.34 million km^2 in March 2020."); World Meteorological Organization (2020) United in Science 2020, 9 ("Arctic (as well as sub-Arctic) sea ice has seen a long-term decline in all months during the satellite era (1979–present), with the largest relative losses in late summer, around the time of the annual minimum in September, with regional variations. The long-term trend over the 1979–2019 period indicates that Arctic summer sea-ice extent has declined at a rate of approximately 13% per decade (Figure 4). In every year from 2016 to 2020, the Arctic average summer minimum and average winter maximum sea-ice extent were below the 1981–2010 long term average. In July 2020, the Arctic sea-ice extent was the lowest on record for July. There is very high confidence that Arctic sea-ice extent continues to decline in all months of the year and that since 1979, the areal proportion of thick ice, at least 5 years old, has declined by approximately 90%."); *and* National Snow & Ice Data Center (2 September 2020) *Tapping the brakes*, Arctic Sea Ice News & Analysis ("As of September 1, Arctic sea ice extent stood at 4.26 million square kilometers (1.64 million square miles), the second lowest extent for that date in the satellite passive microwave record that started in 1979."). Analysis by Zack Labe showed that sea ice for the high Arctic (above 80 ºN) was the lowest extent on record. *See* Zack Labe (@ZLabe), Twitter, 11 September 2020, 6:19pm ("Sea ice extent in the middle of the #Arctic Ocean is currently the lowest on record (e.g., high Arctic ~80°N+ latitude). This is a pretty impressive statistic.").

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

[80] Mallett R. D. C., Stroeve J. C., Cornish S. B., Crawford A. D., Lukovich J. V., Serreze M. C., Barrett A. P., Meier W. N., Heorton H. D. B. S., & Tsamados M. (2021) *Record winter winds in 2020/21 drove exceptional Arctic sea ice transport*, Commun. Earth & Environ. 2: 1–6, 2 ("The response of the sea ice to the wind forcing was such that four times as much MYI area was transported into the Beaufort Sea as was transported out, but the total ice area transported out was double that transported in (Fig. 2a, b). This transport acted to flush the Beaufort Sea of its first-year ice cover and fill it with MYI (Multi-Year Ice). Eight per cent of the Arctic's MYI cover was transported into the Beaufort Sea in winter 2020/2021 (Fig. 2e), contributing to a record fraction of the MYI cover residing in the Beaufort Sea (23.5%) in the last full week of February (Fig. 2f). This fraction has been historically increasing over the data period (1983–2020), however, this high concentration is well above the linear trend (by 2.06 standard deviations; Figs. S9 and S10)."). *See also* Gulev S. K., *et al.* (2021) *Chapter 2: Changing State of the Climate System*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 2-65 ("A reduction of survival rates of sea ice exported from the Siberian shelves by 15% per decade has interrupted the transpolar drift and affected the long-range transport of sea ice (Krumpen et al., 2019). The thinner and on average younger ice has less resistance to

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dynamic forcing, resulting in a more dynamic ice cover (Hakkinen et al., 2008; Spreen et al., 2011; Vihma et al., 2012; Kwok et al., 2013).").

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

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

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

[84] Wang Q., Wekerle C., Wang X., Danilov S., Koldunov N., Sein D., Sidorenko D., von Appen W.-J., & Jung T. (2020) *Intensification of the Atlantic Water Supply to the Arctic Ocean Through Fram Strait Induced by Arctic Sea Ice Decline*, GEOPHYS. RES. LETT. 47(3): e2019GL086682, 1–10, 1 ("The reduction in sea ice export through Fram

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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).").

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

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

[87] 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. RES. 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* Taillant J. D. (2021) *Chapter 5. A Thawing Earth, in* MELTDOWN: THE EARTH WITHOUT GLACIERS, Oxford University Press: Oxford, United Kingdom; *and* Taillant J. D. (2015) *Chapter 4. Invisible Glaciers, in* GLACIERS: THE POLITICS OF ICE, Oxford University Press: Oxford, United Kingdom.

[88] Schaefer K., Lantuit H., Romanovsky V. E., Schuur E. A. G., & Witt R. (2014) *The Impact of the Permafrost Carbon Feedback on Global Climate*, ENVIRON. RES. LETT. 9: 1–9, 2 ("If temperatures rise and permafrost thaws, the organic material will also thaw and begin to decay, releasing carbon dioxide (CO_2) and methane (CH_4) into the atmosphere and amplifying the warming due to anthropogenic greenhouse gas emissions … The PCF is irreversible on human time scales because in a warming climate, the burial mechanisms described above slow down or stop, so there is no way to convert CO_2 into organic matter and freeze it back into the permafrost."). *See also* Schaefer K., Zhang T., Bruhwiler L., & Barrett A. P. (2011) *Amount and timing of permafrost carbon release in response to climate warming*, TELLUS B 63(2): 165–180, 166 ("The permafrost carbon feedback (PCF) is an amplification of surface

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warming due to the release into the atmosphere of carbon currently frozen in permafrost (Fig. 1). As atmospheric CO_2 and methane concentrations increase, surface air temperatures will increase, causing permafrost degradation and thawing some portion of the permafrost carbon. Once permafrost carbon thaws, microbial decay will resume, increasing respiration fluxes to the atmosphere and atmospheric concentrations of CO_2 and methane. This will in turn amplify the rate of atmospheric warming and accelerate permafrost degradation, resulting in a positive PCF feedback loop on climate (Zimov et al., 2006b).”); *and* Chen Y., Liu A., & Moore J.C. (2020) *Mitigation of Arctic permafrost carbon loss through stratospheric aerosol geoengineering*, NAT. COMMUN. 11: 1–35, 2, 3 (“Between 2020 and 2069, PInc-Panther simulations of soil C change, driven by outputs of 7 ESMs for the RCP4.5 projection, varied from 19.4 Pg C gain to 52.7 Pg C loss (mean 25.6 Pg C loss), while under G4 the ensemble mean was 11.9 Pg C loss (range: 29.2 Pg C gain to 44.9 Pg C loss). Projected C losses are roughly linearly proportional to changes in soil temperature, and each 1 °C warming in the Arctic permafrost would result in ~13.7 Pg C loss; the yintercept indicates that the Arctic permafrost, if maintained in current state, would remain a weak carbon sink. MIROC-ESM and MIROC-ESM-CHEM, with simulations of warming above 3°C, produce severe soil C losses, while GISS-E2-R with minor soil temperature change produces net soil C gains under both scenarios before 2070.”; “PIncPanTher simulations of the anoxic respiration rates over the period 2006–2010 are 1.2–1.7 Pg C year−1, and so the estimated range of CH4 emissions is 28–39 Tg year−1, which is very close to the 15–40 Tg CH4 year−1 estimates of current permafrost wetland CH4 emissions.”).

[89] Wilkerson J., Dobosky R., Sayres D. S., Healy C., Dumas E., Baker B., & Anderson J. G. (2019) *Permafrost nitrous oxide emissions observed on a landscape scale using the airborne eddy-covariance method*, ATMOS. CHEM. PHYS. 19(7): 4257–4268, 4257 (“The microbial by-product nitrous oxide (N_2O), a potent greenhouse gas and ozone depleting substance, has conventionally been assumed to have minimal emissions in permafrost regions. This assumption has been questioned by recent in situ studies which have demonstrated that some geologic features in permafrost may, in fact, have elevated emissions comparable to those of tropical soils. However, these recent studies, along with every known in situ study focused on permafrost N_2O fluxes, have used chambers to examine small areas ($< 50\ m^2$). In late August 2013, we used the airborne eddy-covariance technique to make in situ N_2O flux measurements over the North Slope of Alaska from a low-flying aircraft spanning a much larger area: around 310 km^2. We observed large variability of N_2O fluxes with many areas exhibiting negligible emissions. Still, the daily mean averaged over our flight campaign was 3.8 (2.2–4.7) mg $N_2O\ m^{-2}\ d^{-1}$ with the 90 % confidence interval shown in parentheses. If these measurements are representative of the whole month, then the permafrost areas we observed emitted a total of around 0.04–0.09 g m^{-2} for August, which is comparable to what is typically assumed to be the upper limit of yearly emissions for these regions.”).

[90] Biskaborn B. K., *et al.* (2019) *Permafrost is warming at a global scale*, NAT. COMMUN. 10(264): 1–11, 1 (“During the reference decade between 2007 and 2016, ground temperature near the depth of zero annual amplitude in the continuous permafrost zone increased by 0.39 ± 0.15 °C. Over the same period, discontinuous permafrost warmed by 0.20 ± 0.10 °C. Permafrost in mountains warmed by 0.19 ± 0.05 °C and in Antarctica by 0.37 ± 0.10 °C. Globally, permafrost temperature increased by 0.29 ± 0.12 °C.”).

[91] Miner K. R., Turetsky M. R., Malina E., Bartsch A., Tamminen J., McGuire A. D., Fix A., Sweeney C., Elder C. D., & Miller C. E. (2022) *Permafrost carbon emissions in a changing Arctic*, NAT. REV. EARTH ENVIRON. 3: 55–67, 55 (“Permafrost underlies ~25% of the Northern Hemisphere land surface and stores an estimated ~1,700Pg (1,700Gt) of carbon in frozen ground, the active layer and talik[1,2]. Rapid anthropogenic warming and resultant thaw threaten to mobilize permafrost carbon stores[3,4], potentially increasing atmospheric concentrations of carbon dioxide (CO2) and methane (CH4), and converting the Arctic from a carbon sink to a carbon source.”). *See also* Schuur E. A. G., *et al.* (2015) *Climate Change and the Permafrost Carbon Feedback*, NATURE 520: 171–179, 171 (“The first studies that brought widespread attention to permafrost carbon estimated that almost 1,700 billion tons of organic carbon were stored in terrestrial soils in the northern permafrost zone. The recognition of this vast pool stored in Arctic and sub-Arctic regions was in part due to substantial carbon stored at depth (.1 m) in permafrost, below the traditional zone of soil carbon accounting.”); *and* World Bank & International Cryosphere Climate Initiative (2013) ON THIN ICE: HOW CUTTING POLLUTION CAN SLOW WARMING AND SAVE LIVES, 44.

[92] Gulev S. K., *et al.* (2021) *Chapter 2: Changing State of the Climate System*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 2-72 (“Recent (2018–2019) permafrost temperatures in the upper 20–30 m layer (at depths where seasonal variation is minimal) were the highest ever directly observed at

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most sites (Romanovsky et al., 2020), with temperatures in colder permafrost of northern North America being more than 1°C higher than they were in 1978. Increases in temperature of colder Arctic permafrost are larger (average 0.4°C–0.6°C per decade) than for warmer (temperature >–2° C) permafrost (average 0.17°C per decade) of sub-Arctic regions (Figures 2.25, 9.22).").

[93] Canadell J. G., *et al.* (2021) *Chapter 5: Global Carbon and other Biogeochemical Cycles and Feedbacks*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 5-66 ("This new assessment, based on studies included in or published since SROCC (Schaefer et al., 2014; Koven et al., 2015c; Schneider von Deimling et al., 2015; Schuur et al., 2015; MacDougall and Knutti, 2016a; Gasser et al., 2018; Yokohata et al., 2020), estimates that the permafrost CO_2 feedback per degree of global warming (Figure 5.29) is 18 (3.1–41, 5th–95th percentile range) PgC ºC^{-1}. The assessment is based on a wide range of scenarios evaluated at 2100, and an assessed estimate of the permafrost CH_4-climate feedback at 2.8 (0.7–7.3 5th–95th percentile range) Pg C_{eq} ºC^{-1} (Figure 5.29). This feedback affects the remaining carbon budgets for climate stabilisation and is included in their assessment (Section 5.5.2).... Beyond 2100, models suggest that the magnitude of the permafrost carbon feedback strengthens considerably over the period 2100–2300 under a high-emissions scenario (Schneider von Deimling et al., 2015; McGuire et al., 2018). Schneider von Deimling et al., (2015) estimated that thawing permafrost could release 20–40 PgC of CO_2 in the period from 2100 to 2300 under a RCP2.6 scenario, and 115–172 PgC of CO_2 under a RCP8.5 scenario. The multi-model ensemble in (McGuire et al., 2018) project a much wider range of permafrost soil carbon losses of 81–642 PgC (mean 314 PgC) for an RCP8.5 scenario from 2100 to 2300, and of a gain of 14 PgC to a loss of 54 PgC (mean loss of 17 PgC) for an RCP4.5 scenario over the same period... Methane release from permafrost thaw (including abrupt thaw) under high-warming RCP8.5 scenario has been estimated at 836–2614 Tg CH_4 over the 21st century and 2800–7400 Tg CH_4 from 2100–2300 (Schneider von Deimling et al., 2015), and as 5300 Tg CH_4 over the 21st century and 16000 Tg CH_4 from 2100–2300 (Turetsky et al., 2020). For RCP4.5, these numbers are 538–2356 Tg CH_4 until 2100 and 2000-6100 Tg CH_4 from 2100–2300 (Schneider von Deimling et al., 2015), and 4100 Tg CH_4 until 2100 and 10000 Tg CH4 from 2100–2300 (Turetsky et al., 2020).").

[94] 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: 340–344, 340 ("The estimated permafrost area is 15.5 million km^2 using this technique (12.0–18.2 million km^2 using minimum/maximum curves), which compares well to 15.0 million km^2 from observations (12.6–18.4 million km^2)."). *See also* Obu J., *et al.* (2019) *Northern Hemisphere permafrost map based on TTOP modelling for 2000–2016 at 1 km2 scale*, Earth-Sci. Rev. 193: 299–316, 305 ("The best estimate of the permafrost area in the Northern Hemisphere is 13.9 × 10^6 km^2 (14.6% of the exposed land area), representing the total area with where MAGT <0 °C (Fig. 3). The borehole temperature comparison can be used to incorporate uncertainty into this estimate, giving a minimum permafrost extent of 10.1 × 10^6 km^2 (10.5% of exposed land area; the area within MAGT < −2 °C) and a maximum extent of 19.6 × 10^6 km^2 (20.6% of exposed land area; the area within MAGT < +2 °C). The extent of the permafrost region (i.e. all permafrost zones) inferred from permafrost occurrence probabilities is 20.8 × 10^6 km^2 (21.8% of exposed land area). The continuous permafrost zone occupies about half of this area, underlying 10.7 × 10^6 km^2 (11.2% of exposed land area), while the discontinuous (3.1 × 10^6 km^2; 3.3% of exposed land area), sporadic (3.5 × 10^6 km^2; 3.6% of exposed land area), and isolated patches zones (3.5 × 10^6 km^2; 3.6% of exposed land area) almost equally divide the remainder.").

[95] 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: 340–344, 340 ("Under a 1.5 °C stabilization scenario, 4.8 (+2.0, -2.2) million km^2 of permafrost would be lost compared with the 1960–1990 baseline (corresponding to the IPA map, Fig. 1b), and under a 2 °C stabilization we would lose 6.6 (+2.0, -2.2) million km^2, over 40% of the present-day permafrost area. Therefore, stabilizing at 1.5 ºC rather than 2 ºC could potentially prevent approximately 2 million km^2 of permafrost from thawing."). *See also* Burke E.J., Zhang Y., & Krinner G. (2020) *Evaluating permafrost physics in the Coupled Model Intercomparison Project 6 (CMIP6) models and their sensitivity to climate change*, The Cryosphere 14(9): 3155–3174, 3173 ("The CMIP6 models project a loss of permafrost under future climate change of between 1.7 and 2.7×10^6 km^2°C^{-1}. A more impact-relevant statistic is the decrease in annual mean frozen volume (3.0 to 5.3×10^3 km^3°C^{-1}) or around 10 %–40 %°C^{-1}.").

[96] Gasser T., Kechiar M., Ciais P., Burke E.J., Kleinen T., Zhu D., Huang Y., Ekici A., & Obersteiner M. (2018) *Path-dependent reductions in CO_2 emission budgets caused by permafrost carbon release*, Nat. Geosi. 11(11): 830–835,

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833 ("The OSCAR v2.2.1 model, with its new permafrost carbon emulator, estimates future carbon release from thawing permafrost within the range of existing studies (Table 1). A cumulative 60 (11–144)PgC [220 (40–528) GtCO$_2$] is projected to be released by 2100 under RCP8.5, slightly lower than the 37–174PgC [136–638 GtCO$_2$] reviewed by Schuur et al.14, and close to the 28–113PgC [103–414 GtCO$_2$] obtained with a data-constrained model by Koven et al.30"). *Compare with* Rogelj J., *et al.* (2018) *Chapter 2: Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development*, *in* Global Warming of 1.5 °C, *Special Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 96 ("This assessment suggests a remaining budget of about 420 GtCO$_2$ for a two-third chance of limiting warming to 1.5°C.").

[97] Turetsky M. R., Abbott B. W., Jones M. C., Anthony K. W., Olefeldt D., Schuur E. A. G., Grosse G., Kuhry P., Hugelius G., Koven C., Lawrence D. M., Gibson C., Sannel A. B. K., & McGuire A. D. (2020) *Carbon release through abrupt permafrost thaw*, Nat. Geosci. 13: 138–143, 138–139 ("The permafrost zone is expected to be a substantial carbon source to the atmosphere, yet large-scale models currently only simulate gradual changes in seasonally thawed soil. Abrupt thaw will probably occur in <20% of the permafrost zone but could affect half of permafrost carbon through collapsing ground, rapid erosion and landslides. Here, we synthesize the best available information and develop inventory models to simulate abrupt thaw impacts on permafrost carbon balance. Emissions across 2.5 million km^2 of abrupt thaw could provide a similar climate feedback as gradual thaw emissions from the entire 18 million km^2 permafrost region under the warming projection of Representative Concentration Pathway 8.5. While models forecast that gradual thaw may lead to net ecosystem carbon uptake under projections of Representative Concentration Pathway 4.5, abrupt thaw emissions are likely to offset this potential carbon sink. Active hillslope erosional features will occupy 3% of abrupt thaw terrain by 2300 but emit one-third of abrupt thaw carbon losses. Thaw lakes and wetlands are methane hot spots but their carbon release is partially offset by slowly regrowing vegetation. After considering abrupt thaw stabilization, lake drainage and soil carbon uptake by vegetation regrowth, we conclude that models considering only gradual permafrost thaw are substantially underestimating carbon emissions from thawing permafrost..... Our simulations suggest net cumulative abrupt thaw carbon emissions on the order of 80±19PgC by 2300 (Fig. 2a). For context, a recent modelling study found that gradual vertical thaw could result in permafrost carbon losses of 208PgC by 2300 under RCP8.5 (multimodel mean), although model projections ranged from a net carbon gain of 167PgC to a net loss of 641PgC (ref. 2). Thus, our results suggest that abrupt thaw carbon losses are equivalent to approximately 40% of the mean net emissions attributed to gradual thaw. Most of this carbon release stems from newly formed features that cover <5% of the permafrost region").

[98] *Compare* 43 GtCO$_2$e in 2100 with 220 GtCO$_2$ from Gasser *et al.* (2018) for 20% additional emissions. *See* Sayedi S. S., *et al.* (2020) *Subsea permafrost carbon stocks and climate change sensitivity estimated by expert assessment*, Environ. Res. Lett. 15(12): 124075, 1–13, 1 ("We performed a structured expert assessment with 25 permafrost researchers to combine quantitative estimates of the stocks and sensitivity of organic carbon in the subsea permafrost domain (i.e. unglaciated portions of the continental shelves exposed during the last glacial period). Experts estimated that the subsea permafrost domain contains ~560 gigatons carbon (GtC; 170–740, 90% confidence interval) in OM and 45 GtC (10–110) in CH$_4$. Current fluxes of CH$_4$ and carbon dioxide (CO$_2$) to the water column were estimated at 18 (2–34) and 38 (13–110) megatons C yr^{-1}, respectively. Under Representative Concentration Pathway (RCP) RCP8.5, the subsea permafrost domain could release 43 Gt CO$_2$-equivalent (CO$_2$e) by 2100 (14–110) and 190 Gt CO$_2$e by 2300 (45–590), with ~30% fewer emissions under RCP2.6."); *discussed in* (15 February 2021) *Submarine Permafrost Has Been Overlooked as a Major Source of Greenhouse Gases, Scientists Warn*, Yale Environment 360.

[99] Natali S. M., Holdren J. P., Rogers B. M., Treharne R., Duffy P. B., Pomerance R., & MacDonald E. (2021) *Permafrost carbon feedbacks threaten global climate goals*, Proc. Nat'l. Acad. Sci. 118(21): e2100163118, 1–3, 1 ("These nonlinear processes are particularly relevant when considering the pathway to 2 °C—that is, whether mitigation keeps global average temperature increase below 2 °C ("avoidance") or causes an "overshoot" in temperature before stabilizing. Permafrost emissions from gradual thaw alone are highly dependent on both the extent and duration of the temperature overshoot (12). For example, for a 1.5 °C or 2 °C target, an overshoot of 0.5 °C leads to a twofold increase in permafrost emissions, and an overshoot of 1.5 °C leads to a fourfold increase."). *See also* Gasser T., Kechiar M., Ciais P., Burke E. J., Kleinen T., Zhu D., Huang Y., Ekici A., & Obersteiner M. (2018) *Path-dependent reductions in CO$_2$ emission budgets caused by permafrost carbon release*, Nat. Geosci. 11(11): 830–835, 833 ("In the case of an overshoot amplitude of 0.5 °C, emissions from permafrost thaw reduce the net emission budgets by 130 (30–300) GtCO$_2$ for the 1.5 °C long-term target (that is for a peak temperature of 2 °C, a case that corresponds to the Paris Climate Agreement), and by 190 (50–400)GtCO$_2$ for the 2 °C target (Fig. 2a). For an overshoot amplitude

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of 1 °C, permafrost-induced reductions reach 210 (50–430)GtCO$_2$ for the 1.5 °C target, and 270 (70–530)GtCO$_2$ for 2 °C target. (Budgets for other targets and other levels of overshoot are provided in Fig. 2 and Supplementary Table 1.)”).

[100] Froitzheim N., Majka J., & Zastrozhnov D. (2021) *Methane release from carbonate rock formations in the Siberian permafrost area during and after the 2020 heat wave*, PROC. NAT'L. ACAD. SCI. 118(32): 1–3, 1 (“In the Taymyr Peninsula and surroundings in North Siberia, the area of the worldwide largest positive surface temperature anomaly for 2020, atmospheric methane concentrations have increased considerably during and after the 2020 heat wave. Two elongated areas of increased atmospheric methane concentration that appeared during summer coincide with two stripes of Paleozoic carbonates exposed at the southern and northern borders of the Yenisey-Khatanga Basin, a hydrocarbon-bearing sedimentary basin between the Siberian Craton to the south and the Taymyr Fold Belt to the north. Over the carbonates, soils are thin to nonexistent and wetlands are scarce. The maxima are thus unlikely to be caused by microbial methane from soils or wetlands. We suggest that gas hydrates in fractures and pockets of the carbonate rocks in the permafrost zone became unstable due to warming from the surface. This process may add unknown quantities of methane to the atmosphere in the near future.”). *Discussed in* Carrington D. (2 August 2021) *Climate crisis: Siberian heatwave led to new methane emissions, study says*, THE GUARDIAN (“The Siberian heatwave of 2020 led to new methane emissions from the permafrost, according to research. Emissions of the potent greenhouse gas are currently small, the scientists said, but further research is urgently needed. Analysis of satellite data indicated that fossil methane gas leaked from rock formations known to be large hydrocarbon reservoirs after the heatwave, which peaked at 6C above normal temperatures. Previous observations of leaks have been from permafrost soil or under shallow seas.”), *and* Mufson S. (3 August 2021) *Scientists expected thawing wetlands in Siberia's permafrost. What they found is 'much more dangerous'*, WASHINGTON POST.

[101] Permafrost Pathways, *Course of Action: Mitigation Policy* (*last visited* 9 May 2022) (“Depending on how hot we let it get, carbon emissions from Arctic permafrost thaw are expected to be in the range of 30 to more than 150 billion tons of carbon (110 to more than 550 Gt CO$_2$) this century, with upper estimates on par with the cumulative emissions from the entire United States at its current rate. To put it another way, permafrost thaw emissions could use up between 25 and 40 percent of the remaining carbon budget that would be necessary to cap warming at the internationally agreed-upon 2 degrees Celsius global temperature threshold established in the Paris Agreement…. Despite the enormity of this problem, gaps in permafrost carbon monitoring and modeling are resulting in permafrost being left out of global climate policies, rendering our emissions targets fundamentally inaccurate. World leaders are in a race against time to reduce emissions and prevent Earth's temperature from reaching dangerous levels. The problem is, without including current and projected emissions from permafrost, this race will be impossible to finish…. 82% [o]f IPCC models do not include carbon emissions from permafrost thaw.”).

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

[103] DeGeorge K. (29 June 2021) *The looming Arctic collapse: More than 40% of north Russian buildings are starting to crumble*, ARCTIC TODAY. (“Aleksandr Kozlov, Russia's Minister of Natural Resources, told a minister's council in May that more than 40% of the northern region's buildings are starting to deform. Nearly 30% of oil and gas

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installations are inoperable. By 2050, Russian researchers estimate that the melting permafrost will inflict damages worth about $69 billion, about a quarter of the current Russian federal budget.”).

[104] Wadhams P. (2017) A FAREWELL TO ICE: A REPORT FROM THE ARCTIC, Oxford University Press: Oxford, United Kingdom. *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.

[105] Whiteman G., Hope C., & Wadhams P. (2013) *Vast costs of Arctic change*, NATURE 499(7459): 401–403, 401 (“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 ….”).

[106] Steinbach J., Holmstrand H., Shcherbakova K., Kosmach D., Brüchert V., Shakhova N., Salyuk A., Sapart C. J., Chernykh D., Noormets R., Semiletov I., & Gustafsson Ö. (2021) *Source apportionment of methane escaping the subsea permafrost system in the outer Eurasian Arctic Shelf*, PROC. NAT’L. ACAD. SCI. 118(10): 1–9, 7 (“Taken together, the triple-isotope data presented here, in combination with other system data and indications from earlier studies, suggest that deep thermogenic reservoirs are key sources of the elevated methane concentrations in the outer Laptev Sea. This finding is essential in several ways: The occurrence of elevated levels of radiocarbon-depleted methane in the water column may be an indication of thawing subsea permafrost in the study area (see also ref. 8). The triple-isotope fingerprinting suggests, however, that methane may not primarily originate directly from the subsea permafrost; the continuous leakage of an old geological reservoir to the water column suggests the existence of perforations in the subsea permafrost, serving as conduits of deeper methane to gas-charged shallow sediments. Second, the finding that methane is released from a large pool of preformed methane, as opposed to methane from slow decomposition of thawing subsea permafrost organic matter, suggests that these releases may be more eruptive in nature, which provides a larger potential for abrupt future releases.”).

[107] 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_4 emissions from old permafrost carbon range from 0 to 53 Tg CH_4 per year (table S10) (20) throughout the last deglaciation and may have contributed up to 27% of the total CH_4 emissions to the atmosphere (95% CI upper limit) at the end of the OD-B transition (14.42 ka BP). However, we consider this calculation speculative (see section 4.3 of the materials and methods) (20)…. The last deglaciation serves only as a partial analog to current anthropogenic warming, with the most important differences being the much colder baseline temperature, lower sea level, and the presence of large ice sheets covering a large part of what are currently permafrost regions in the NH…. Because the relatively large global warming of the last deglaciation (which included periods of large and rapid regional warming in the high latitudes) did not trigger CH_4 emissions from old carbon reservoirs, such CH_4 emissions in response to anthropogenic warming also appear to be unlikely.”). *See also* Intergovernmental Panel on Climate Change (2021) *Climate Change 2021: The Physical Science Basis* Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. 5-80 (” The present-day methane release from shelf clathrates is <10 TgCH4 yr-1 (Kretschmer et al., 2015; Saunois et al., 2020). Despite polar amplification (Chapter 7), substantial releases from the permafrost-embedded subsea clathrates is very unlikely (Minshull et al., 2016; Malakhova and Eliseev, 2017, 2020). This is consistent with an overall small release of methane from the shelf clathrates during the last deglacial despite large reorganisations in climate state (Bock et al., 2017; Petrenko et al.,

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2017; Dyonisius et al., 2020). The long timescales associated with clathrate destabilisation makes it unlikely that CH4 release from the ocean to the atmosphere will deviate markedly from the present-day value through the 21st century (Hunter et al., 2013), corresponding to no more than additional 20 ppb of atmospheric methane (i.e. <0.2 ppb yr-1 52).").

[108] 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*, Comment, NATURE, 575(7784): 592–595, 593 ("A further key impetus to limit warming to 1.5 °C is that other tipping points could be triggered at low levels of global warming. The latest IPCC models projected a cluster of abrupt shifts between 1.5 °C and 2 °C, several of which involve sea ice. This ice is already shrinking rapidly in the Arctic….").

[109] Hoegh-Guldberg O., *et al.* (2018) *Chapter 3: Impacts of 1.5 ºC of Global Warming on Natural and Human Systems*, *in* GLOBAL WARMING OF 1.5 °C, *Special Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 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.").

[110] Abram N., *et al.* (2019) *Chapter 1: Framing and Context of the Report*, *in* THE OCEAN AND CRYOSPHERE IN A CHANGING CLIMATE, *Special Report of the Intergovernmental Panel on Climate Change*, Pörtner H.-O., *et al.* (eds.), 81 ("While some aspects of the ocean and cryosphere might respond in a linear (i.e., directly proportional) manner to a perturbation by some external forcing, this may change fundamentally when critical thresholds are reached. A very important example for such a threshold is the transition from frozen water to liquid water at around 0 ºC that can lead to rapid acceleration of ice-melt or permafrost thaw (e.g., Abram et al., 2013; Trusel et al., 2018). Such thresholds often act as tipping points, as they are associated with rapid and abrupt changes even when the underlying forcing changes gradually (Figure 1.1a, 1.1c). Tipping elements include, for example, the collapse of the ocean's large-scale overturning circulation in the Atlantic (Section 6.7), or the collapse of the West Antarctic Ice Sheet though a process called marine ice sheet instability (Cross-Chapter Box 8 in Chapter 3; Lenton, *et al.* 2008). Potential ocean and cryosphere tipping elements form part of the scientific case for efforts to limit climate warming to well below 2ºC (IPCC, 2018)."). *See also* Collins M., *et al.* (2019) *Chapter 6: Extreme, Abrupt Changes and Managing Risk*, *in* THE OCEAN AND CRYOSPHERE IN A CHANGING CLIMATE, *Special Report of the Intergovernmental Panel on Climate Change*, Pörtner H.-O., *et al.* (eds.), 595–596 (Table 6.1).

[111] Boers N. & Rypdal M. (2021) *Critical slowing down suggests that the western Greenland Ice Sheet is close to a tipping point*, PROC. NAT'L. ACAD. SCI. 118(21): 1–7, 1 ("A crucial nonlinear mechanism for the existence of this tipping point is the positive melt-elevation feedback: Melting reduces ice sheet height, exposing the ice sheet surface to warmer temperatures, which further accelerates melting. We reveal early-warning signals for a forthcoming critical transition from ice-core-derived height reconstructions and infer that the western Greenland Ice Sheet has been losing stability in response to rising temperatures. We show that the melt-elevation feedback is likely to be responsible for the observed destabilization. Our results suggest substantially enhanced melting in the near future.").

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[112] 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.").

[113] 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*, Comment, NAT. CLIM. CHANGE, 10: 879–881, 881 ("In AR5, the ice-sheet contribution by 2100 is forecast from process-based models simulating changes in ice flow and surface mass balance (SMB) in response to climate warming. Driven by the century-scale increase in temperature forced by representative concentration pathways (RCPs), global mean SLR estimates range from 280–980 mm by 2100 (Fig. 1). Of this, the ice-sheet contribution constitutes 4–420 mm (ref. 3). The spread of these scenarios is uncertain, scenario-dependent and increases rapidly after 2030 (Fig. 1). During 2007–2017, satellite observations show total ice-sheet losses increased the global sea level by 12.3 ± 2.3 mm and track closest to the AR5 upper range (13.7–14.1 mm for all emissions pathways) (Fig. 1). Despite a reduction in ice-sheet losses during 2013–2017 — when atmospheric circulation above Greenland promoted cooler summer conditions and heavy winter snowfall2 — the observed average SLR rate (1.23 ± 0.24 mm per year) is 45% above central predictions (0.85 ± 0.07 mm per year) and closest to the upper range (1.39 ± 0.14 mm per year) (Fig. 2)."). In mid-September 2020, consistent warming over northeast Greenland contributed to a large chunk of a glacier breaking away from the Arctic's largest remaining ice shelf. *See* Amos J. (14 September 2020) *Climate change: Warmth shatters section of Greenland ice shelf*, BBC NEWS ("A big chunk of ice has broken away from the Arctic's largest remaining ice shelf - 79N, or Nioghalvfjerdsfjorden - in north-east Greenland. The ejected section covers about 110 square km; satellite imagery shows it to have shattered into many small pieces. The loss is further evidence say scientists of the rapid climate changes taking place in Greenland. … At its leading edge, the 79N glacier splits in two, with a minor offshoot turning directly north. It's this offshoot, or tributary, called Spalte Glacier, that has now disintegrated. The ice feature was already heavily fractured in 2019; this summer's warmth has been its final undoing. Spalte Glacier has become a flotilla of icebergs.").

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

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climate change than previously thought. We estimate that the warming threshold leading to a monostable, essentially ice-free state is in the range of 0.8–3.2 ºC, with a best estimate of 1.6 ºC. By testing the ice sheet's ability to regrow after partial mass loss, we find that at least one intermediate equilibrium state is possible, though for sufficiently high initial temperature anomalies, total loss of the ice sheet becomes irreversible. Crossing the threshold alone does not imply rapid melting (for temperatures near the threshold, complete melting takes tens of millennia). However, the timescale of melt depends strongly on the magnitude and duration of the temperature overshoot above this critical threshold."). *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."); Schleussner C.-F., Lissner T. K., Fischer E. M., Wohland J., Perrette M., Golly A., Rogelj J., Childers K., Schewe J., Frieler K., Menge M., Hare W., & Schaeffer M. (2016) *Differential Climate Impacts for Policy-Relevant Limits to Global Warming: the Case of 1.5ºC and 2ºC*, Earth Syst. Dynam. 7(2): 327–351, 342 ("In addition to that, Levermann et al. (2013) report a steep increase in long-term SLR between 1.5 ºC and 2 ºC as a result of an increasing risk of crossing a destabilizing threshold for the Greenland ice-sheet (Robinson et al., 2012). The disintegration process that would lead to 5–7m global SLR, however, is projected to happen on the timescale of several millennia."); *and* Kopp R. E., Shwon R. L., Wagner G., & Yuan J. (2016) *Tipping elements and climate–economic shocks: Pathways toward integrated assessment*, Earth's Future 4(8): 346–372, 354–355 ("For the Greenland Ice Sheet, for example, feedbacks between ice sheet topography and atmospheric dynamics and between ice area and albedo give rise to multiple stable states [*Ridley et al*., 2009; *Robinson et al*., 2012; *Levermann et al*., 2013]. *Robinson et al*. [2012]'s coupled ice-sheet/regional climate model indicated that, at a temperature of 1ºC above pre-Industrial temperatures, the stable states are at 100%, 60%, and 20% of present ice volume. At 1.6ºC, however, their model produced only one stable configuration, at ~15% of the Greenland ice sheet's present volume; thus, 1.6ºC warming would represent a commitment to ~6 m of sea-level rise from the Greenland Ice Sheet. The rate of ice sheet mass loss is, however, limited by the flux at the ice sheet margins [e.g., *Pfeffer et al*., 2008], leading to a disconnect between committed and realized change that could persist for millennia, particularly for levels of warming near the threshold [*Applegate et al*., 2015]."). If warming is limited to 2 ºC, 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 ºC, 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).

[115] DeConto R. M., Pollard D., Alley R. B., Velicogna I., Gasson E., Gomez N., Sadai S., Condron A., Gilford D. M., Ashe E. L., Kopp R. E., Li D., & Dutton A. (2021) *The Paris Climate Agreement and future sea-level rise from Antarctica*, Nature 593(7857): 83–89, 88 ("We find that without future warming beyond 2020, Antarctica continues to contribute to 21st-century sea-level rise at a rate roughly comparable to today's, producing 5 cm of GMSL (Global Mean Sea Level) rise by 2100 and 1.34 m by 2500 (Fig. 3, Table 1). Simulations initially following the +3 °C pathway, but with subsequent CDR (carbon dioxide reduction/negative emissions) delayed until after 2060, show a sharp jump in the pace of 21st-century sea-level rise (Fig. 3b). Every decade that CDR mitigation is delayed has a substantial long-term consequence on sea level, despite the fast decline in CO_2 and return to cooler temperatures (Fig. 3c). Once initiated, marine-based ice loss is found to be unstoppable on these timescales in all mitigation scenarios (Fig. 3). The commitment to sustained ice loss is caused mainly by the onset of marine ice instabilities triggered by the loss of ice shelves that cannot recover in a warmer ocean with long thermal memory (Fig. 3c)."). *See also* Pattyn F., *et al.* (2018) *The Greenland and Antarctic ice sheets under 1.5 °C global warming*, Nat. Clim. Change 8(12): 1053–1061, 1053 ("On millennial timescales, both ice sheets have tipping points at or slightly above the 1.5–2.0 °C threshold; for Greenland, this may lead to irreversible mass loss due to the surface mass balance–elevation feedback, whereas for Antarctica, this could result in a collapse of major drainage basins due to ice-shelf weakening.").

[116] Fox-Kemper B., *et al.* (2021) *Chapter 9: Ocean, Cryosphere and Sea Level Change*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 9-122, 9-116 ("the main uncertainty related to high-end sea-level rise is "when" rather than "if" it arises: the upper limit of 1.02 m of *likely* sea-level range by 2100 for the SSP 5-8.5 scenario will be exceeded in any future warming scenario on time scales of centuries to millennia (*high confidence*), but it is uncertain how quickly the long-term committed sea level will be reached (Section 9.6.3.5). Hence, global-mean sea level might rise well above the *likely* range before 2100, which is reflected by

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assessments of ice-sheet contributions based on structured expert judgment (Bamber et al., 2019) leading to a 95th percentile of projected future sea-level rise as high as 2.3 m in 2100 (Section 9.6.3.3)… High-end sea-level rise can therefore occur if one or two processes related to ice-sheet collapse in Antarctica result in an additional sea-level rise at the maximum of their plausible ranges (Sections 9.4.2.5, 9.6.3.3; Table 9.7) or if several of the processes described in this box result in individual contributions to additional sea-level rise at moderate levels. In both cases, global-mean sea-level rise by 2100 would be substantially higher than the assessed *likely* range, as indicated by the projections including *low confidence* processes reaching in 2100 as high as 1.6 m at the 83rd percentile and 2.3 m at the 95th percentile (Section 9.6.3.3)."; "While ice-sheet processes in whose projection there is *low confidence* have little influence up to 2100 on projections under SSP1-1.9 and SSP1-2.6 (Table 9.9), this is not the case under higher emissions scenarios, where they could lead to GMSL rise well above the *likely* range. In particular, under SSP5-8.5, *low confidence* processes could lead to a total GMSL rise of 0.6-1.6 m over this time period (17th-83rd percentile range of p-box including SEJ- and MICI-based projections), with 5th-95th percentile projections extending to 0.5-2.3 m (*low confidence*).").

[117] Ripple W. J., Wolf C., Newsome T. M., Gregg J. W., Lenton T. M., Palomo I., Eikelboom J. A. J., Law B. E., Huq S., Duffy P. B., & Rockström J. (2021) *World Scientists' Warning of a Climate Emergency 2021*, BIOSCIENCE: 1–5, 3 ("Greenland and Antarctica recently showed new year-to-date alltime record low levels of ice mass (figure 2f, 2g). In 2020, the minimum summer Arctic sea ice was at its second smallest extent on record, and glacier thickness also set a new all-time low (figure 2e, 2h). Glaciers are melting much faster than previously believed; they are losing 31% more snow and ice per year than they did just 15 years ago (Hugonnet et al. 2021).").

[118] Ramirez R. (30 July 2021) *The amount of Greenland ice that melted on Tuesday could cover Florida in 2 inches of water*, CNN.

[119] National Snow & Ice Data Center (18 August 2021) *Rain at the summit of Greenland*, GREENLAND ICE SHEET TODAY.

[120] Boers N. (2021) *Observation-based early-warning signals for a collapse of the Atlantic Meridional Overturning Circulation*, NAT. CLIM. CHANGE 11(8): 680–688. 687 ("The results presented here hence show that the recently discovered AMOC decline during the last decades is not just a fluctuation related to low-frequency climate variability or a linear response to increasing temperatures. Rather, the presented findings suggest that this decline may be associated with an almost complete loss of stability of the AMOC over the course of the last century, and that the AMOC could be close to a critical transition to its weak circulation mode.").

[121] Douville H., *et al.* (2021) *Chapter 8: Water Cycle Changes*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 8-111 ("These patterns of past hydroclimatic change are relevant for future projections because it is *very likely* that AMOC will weaken by 2100 in response to increased greenhouse gas emissions (Weaver et al., 2012; Drijfhout et al., 2015; Bakker et al., 2016; Reintges et al., 2017) (See also Section 9.2.3.1). Furthermore, there is *medium confidence* that the decline in AMOC will not involve an abrupt collapse before 2100 (Section 9.2.3.1)."). *See also* Arias P. A., *et al.* (2021) *Technical Summary*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), TS-39 ("While there is *medium confidence* that the projected decline in the Atlantic Meridional Overturning Circulation (AMOC) (TS.2.4) will not involve an abrupt collapse before 2100, such a collapse might be triggered by an unexpected meltwater influx from the Greenland Ice Sheet. If an AMOC collapse were to occur, it would *very likely* cause abrupt shifts in the weather patterns and water cycle, such as a southward shift in the tropical rain belt, and could result in weakening of the African and Asian monsoons and strengthening of Southern Hemisphere monsoons. {4.7.2, 8.6.1, 9.2.3, Box TS.9, Box TS.13}"); *and* Fox-Kemper B., *et al.* (2021) *Chapter 9: Ocean, Cryosphere and Sea Level Change*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 9-33 ("Both the AR5 (Collins et al., 2013) and the SROCC (Collins et al., 2019) assessed that an abrupt collapse of the AMOC before 2100 was *very unlikely*, but the SROCC added that by 2300 an AMOC collapse was *as likely as not* for high-emission scenarios. The SROCC also assessed that model-bias may considerably affect the sensitivity of the modelled AMOC to freshwater forcing. Tuning towards stability and model biases (Valdes, 2011; Liu et al., 2017; Mecking et al., 2017; Weijer et al., 2019) provides CMIP models a tendency toward unrealistic stability (*medium confidence*). By correcting for existing salinity biases,

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Liu et al. (2017) demonstrated that AMOC behaviour may change dramatically on centennial to millennial timescales and that the probability of a collapsed state increases. None of the CMIP6 models features an abrupt AMOC collapse in the 21st century, but they neglect meltwater release from the Greenland ice sheet and a recent process study reveals that a collapse of the AMOC can be induced even by small-amplitude changes in freshwater forcing (Lohmann and Ditlevsen, 2021). As a result, we change the assessment of an abrupt collapse before 2100 to *medium confidence* that it will not occur.”).

[122] Douville H., *et al*. (2021) *Chapter 8: Water Cycle Changes*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 8-112 (“As with the paleoclimate events, AMOC collapse results in a southward shift in the ITCZ that is most pronounced in the tropical Atlantic. This could cause drying in the Sahel region (Defrance et al., 2017) as well as Mesoamerica and northern Amazonia (Parsons et al., 2014; Chen et al., 2018c). AMOC collapse also causes the Asian monsoon systems to weaken (Liu et al., 2017b) (Figure 8.27b) counteracting the strengthening expected in response to elevated greenhouse gases (see Section 8.4.2). Europe is projected to experience moderate drying in response to AMOC collapse (Jackson et al., 2015)”). *Discussed in* Velasquez-Manoff M. & White J. (3 March 2021) *In the Atlantic Ocean, Subtle Shifts Hint at Dramatic Dangers*, The New York Times (“The consequences could include faster sea level rise along parts of the Eastern United States and parts of Europe, stronger hurricanes barreling into the Southeastern United States, and perhaps most ominously, reduced rainfall across the Sahel, a semi-arid swath of land running the width of Africa that is already a geopolitical tinderbox.”).

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

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

[125] Morlighem M., et al. (2020) *Deep glacial troughs and stabilizing ridges unveiled beneath the margins of the Antarctic ice sheet*, Nat. Geosci. 13: 132–137; *discussed in* *ThwaitesGlacier.org* (*last accessed* 2 May 2022) (“**7. Thwaites Glacier ice loss currently contributes around 4% of all global sea-level rise** (assuming 3.5 mm annual sea-level rise) and has the potential to contribute significantly more.”).

[126] Groh A., & Horwath M. (2021) *Antarctic Ice Mass Change Products from GRACE/GRACE-FO Using Tailored Sensitivity Kernels*, Remote Sens. 13(9); *discussed in* *ThwaitesGlacier.org* (*last accessed* 2 May 2022) (“**10. Since 2000, the glacier has had a net loss of more than 1000 billion tons of ice.** *(Source and calculation:)* *https://data1.geo.tu-dresden.de/ais_gmb/* *Over the period 2002–2016 (14 years), Basin AIS21, which is slightly larger than just TG, has lost a total of 748 Gt. Assuming the last 4 years lost ice at the same rate gives a total of 1068 Gt.)*”).

[127] Witze A. (11 January 2022) *Giant cracks push imperilled Antarctic glacier closer to collapse*, Nature News (“The fractures are propagating through the ice at speeds of several kilometres per year. They are heading into weaker and thinner ice, where they could accelerate and lead to the demise of this part of the ice shelf within five years, Pettit estimates.”). *See also* Gilbert E. (3 January 2022) *What Antarctica's 'Doomsday' Glacier Could Mean For The World*,

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Science Alert ("But scientists have just confirmed that this ice shelf is becoming rapidly destabilized. The eastern ice shelf now has cracks crisscrossing its surface and could collapse within ten years, according to Erin Pettit, a glaciologist at Oregon State University. This work supports research published in 2020 which also noted the development of cracks and crevasses on the Thwaites ice shelf. These indicate that it is being structurally weakened. This damage can have a reinforcing feedback effect because cracking and fracturing can promote further weakening, priming the ice shelf for disintegration."); *and* Scambos T. & Weeman K. (13 December 2021, updated 31 January 2022) *The Threat from Thwaites: The Retreat of Antarctica's Riskiest Glacier*, Cooperative Institute for Research in Environmental Sciences ("Thwaites sits in West Antarctica, flowing across a 120km stretch of frozen coastline. A third of the glacier, along its eastern side, flows more slowly than the rest—it's braced by a floating ice shelf, a floating extension of the glacier that is held in place by an underwater mountain. The ice shelf acts like a brace that prevents faster flow of the upstream ice. But the brace of ice slowing Thwaites won't last for long, said Erin Petitt, an associate professor at Oregon State University. Beneath the surface, warmer ocean water circulating beneath the floating eastern side is attacking this glacier from all angles, her team has found. This water is melting the ice directly from beneath, and as it does so, the glacier loses its grip on the underwater mountain. Massive factures have formed and are growing as well, accelerating its demise, said Pettit. This floating extension of the Thwaites Glacier will likely survive only a few more years."; "The "chain reaction," beginning with the potential collapse of Thwaites' Eastern Ice Shelf would set in motion a long-term process which would eventually result in global sea level rise. While the initial steps of ice shelf collapse, glacier speed-up, and increased ice-cliff failure might happen within a couple of decades, the "2 to 10 feet" of sea level rise will require centuries to unfold—and impacts can still be mitigated depending on how humans respond in coming decades. Risk of multiple feet of sea level rise will not happen this decade (and likely not even in the next few decades).").

[128] 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).").

[129] Solomon S., Daniel J. S., Sanford T. J., Murphy D. M., Plattner G.-K., Knutti R., & Friedlingstein P. (2010) *Persistence of climate changes due to a range of greenhouse gases*, Proc. Nat'l. Acad. Sci. 107(43): 18354–18359, 18357 ("In the case of a gas with a 10-y lifetime, for example, energy is slowly stored in the ocean during the period when concentrations are elevated, and this energy is returned to the atmosphere from the ocean after emissions cease and radiative forcing decays, keeping atmospheric temperatures somewhat elevated for several decades. Elevated temperatures last longer for a gas with a 100-y lifetime because, in this case, radiative forcing and accompanying further ocean heat uptake continue long after emissions cease. As radiative forcing decays further, the energy is ultimately restored from the ocean to the atmosphere. Fig. 3 shows that the slow timescale of ocean heat uptake has two important effects. It limits the transfer of energy to the ocean if emissions and radiative forcing occur only for a few decades or a century. However, it also implies that any energy that is added to the ocean remains available to be transferred back to the atmosphere for centuries after cessation of emissions."). *See also* MacDougall A. H., *et al.* (2020) *Is there warming in the pipeline? A multi-model analysis of the Zero Emissions Commitment from CO2*, Biogeosci. 17(11): 2987–3016, 3003 ("Overall, the most likely value of ZEC on decadal timescales is assessed to be close to zero, consistent with prior work. However, substantial continued warming for decades or centuries following cessation of emissions is a feature of a minority of the assessed models and thus cannot be ruled out purely on the basis of models.").

[130] Arias P. A., *et al.* (2021) *Technical Summary*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), TS-40 ("It is *virtually certain* that the global ocean has warmed since at least 1971, representing about 90% of the increase in the global energy inventory (TS.3.1). The ocean is currently warming faster than at any other time since at least the last deglacial transition (*medium confidence*), with warming extending to depths well below 2000 m (*very high confidence*). It is *extremely likely* that human influence was the main driver of ocean warming. Ocean warming will continue over the 21st century (*virtually certain*), and will *likely* continue until at least to 2300 even for low CO$_2$ emissions scenarios. Ocean warming is irreversible over centuries to millennia (*medium confidence*), but the magnitude of warming is scenario-dependent from about the mid-21st century (*medium confidence*)... Global mean SST has increased since the beginning of the 20th century by 0.88 [0.68 to 1.01] °C, and it is *virtually certain* it will continue to increase throughout the 21st century with increasing hazards to marine ecosystems (*medium confidence*). Marine heatwaves have become more frequent over the 20th century (*high*

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confidence), approximately doubling in frequency (*high confidence*) and becoming more intense and longer since the 1980s (*medium confidence*).”).

[131] Dreyfus G. B., Xu Y., Shindell D. T., Zaelke D., & Ramanathan V. (2022) *Mitigation climate disruption in time: A self-consistent approach for avoiding both near-term and long-term global warming*, Proc. Nat’l. Acad. Sci. (*in press*) (“We find that mitigation measures that target only decarbonization are essential for strong long-term cooling but can result in weak near-term warming (due to unmasking the cooling effect of co-emitted aerosols) and lead to temperatures exceeding 2°C before 2050. In contrast, pairing decarbonization with additional mitigation measures targeting short-lived climate pollutants (SLCPs) and N_2O, slows the rate of warming a decade or two earlier than decarbonization alone and avoids the 2°C threshold altogether. These non-CO_2 targeted measures when combined with decarbonization can provide net cooling by 2030, reduce the rate of warming from 2030 to 2050 by about 50%, roughly half of which comes from methane, significantly larger than decarbonization alone over this timeframe.”). *See also* Intergovernmental Panel on Climate Change (2022) *Summary for Policymakers*, *in* Climate Change 2022: Mitigation of Climate Change, *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Shukla P. R., *et al.* (eds.), SPM-31 (“In modelled global low emission pathways, the projected reduction of cooling and warming aerosol emissions over time leads to net warming in the near- to mid-term. In these mitigation pathways, the projected reductions of cooling aerosols are mostly due to reduced fossil fuel combustion that was not equipped with effective air pollution controls.”); Naik V., *et al.* (2021) *Chapter 6: Short-lived climate forcers*, in Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 6-8 (“Additional CH_4 and BC mitigation would contribute to offsetting the additional warming associated with SO_2 reductions that would accompany decarbonization (*high confidence*).”); Ramanathan V. & Feng Y. (2008) *On avoiding dangerous anthropogenic interference with the climate system: Formidable challenges ahead*, Proc. Nat’l. Acad. Sci. 105(38): 14245–14250, 14248 (“Switching from coal to ‘‘cleaner’’ natural gas will reduce CO_2 emission and thus would be effective in minimizing future increases in the committed warming. However, because it also reduces air pollution and thus the ABC [Atmospheric Brown Cloud] masking effect, it may speed up the approach to the committed warming of 2.4°C (1.4–4.3°C).”); *and* United Nations Environment Programme & World Meteorological Organization (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone, 254 (“Evaluating global mean temperature change, it was found that the targeted measures to reduce emissions of methane and BC could greatly reduce warming rates over the next few decades (Figure 6.1; Box 6.1). When all measures are fully implemented, warming during the 2030s relative to the present would be only half as much as in the reference scenario. In contrast, even a fairly aggressive strategy to reduce CO_2 emissions, as for the CO_2-measures scenario, does little to mitigate warming until after the next 20-30 years (Box 6.2). In fact, sulphur dioxide (SO_2) is coemitted with CO_2 in some of the most highly emitting activities, coal burning in large-scale combustion such as in power plants, for example, that are obvious targets for reduced usage under a CO_2-emissions mitigation strategy. Hence such strategies can lead to additional near-term warming (Figure 6.1), in a well-known temporary effect (e.g. Raes and Seinfeld, 2009), although most of the nearterm warming is driven by CO_2 emissions in the past. The CO_2-measures scenario clearly leads to long-term benefits however, with a dramatically lower warming rate at 2070 under that scenario than under the scenario with only CH_4 and BC measures (see Figure 6.1 and timescales in Box 6.2). Hence the near-term measures clearly cannot be substituted for measures to reduce emissions of long-lived GHGs. The near-term measures largely target different source sectors for emissions than the CO_2 measures, so that the emissions reductions of the short-lived pollutants are almost identical regardless of whether the CO_2 measures are implemented or not, as shown in Chapter 5. The near-term measures and the CO_2 measures also impact climate change over different timescales owing to the different lifetimes of these substances. In essence, the near-term CH_4 and BC measures are effectively uncoupled from CO_2 measures examined here.”).

[132] Climate scientist and IPCC author Joeri Rogelj, *as quoted in* Berwyn B. (15 September 2021) *The Rate of Global Warming During Next 25 Years Could Be Double What it Was in the Previous 50, a Renowned Climate Scientist Warns*, Inside Climate News (“James Hansen, a climate scientist who shook Washington when he told Congress 33 years ago that human emissions of greenhouse gases were cooking the planet, is now warning that he expects the rate of global warming to double in the next 20 years. While still warning that it is carbon dioxide and methane that are driving global warming, Hansen said that, in this case, warming is being accelerated by the decline of other industrial pollutants that they’ve cleaned from it…. In Hansen’s latest warning, he said scientists are dangerously underestimating the climate impact of reducing sulfate aerosol pollution. ‘Something is going on in addition to greenhouse warming,’ Hansen wrote, noting that July’s average global temperature soared to its second-highest reading on record even though the Pacific Ocean is in a cooling La Niña phase that temporarily dampens signs of

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warming. Between now and 2040, he wrote that he expects the climate's rate of warming to double in an 'acceleration that can be traced to aerosols.' That acceleration could lead to total warming of 2 degrees Celsius by 2040, the upper limit of the temperature range that countries in the Paris accord agreed was needed to prevent disastrous impacts from climate change. What's more, Hansen and other researchers said the processes leading to the acceleration are not adequately measured, and some of the tools needed to gauge them aren't even in place…. A doubling of the rate of global warming would put the planet in the fast lane of glacial melting, sea level rise and coral reef ecosystem die-offs, as well as escalating heatwaves, droughts and floods. But that future is not yet set in stone, said Michael Mann, a climate scientist at Penn State. He said Hansen's prediction appears inconsistent with the scientific literature assessed by the Intergovernmental Panel on Climate Change. The IPCC's latest report advises "that reductions of carbon emissions by 50 percent over the next decade and net-zero by 2100, along with a ramp-down in both aerosols and other short-term agents, including black carbon and other trace anthropogenic greenhouse gases, stabilizes warming well below 2 degrees Celsius," Mann said. But the IPCC report also highlighted that declining aerosol pollution will speed warming. "The removal of air pollution, either through air quality measures or because combustion processes are phased out to get rid of CO2, will result in an increase in the resulting rate of warming," said climate scientist and IPCC report author Joeri Rogelj, director of research at the Imperial College London's Grantham Institute. There's a fix for at least some of this short-term increase in the rate of warming, he said. "The only measures that can counteract this increased rate of warming over the next decades are methane reductions," Rogelj said. "I just want to highlight that methane reductions have always been part of the portfolio of greenhouse gas emissions reductions that are necessary to meet the goals of the Paris Agreement. This new evidence only further emphasizes this need.").

[133] Lelieveld J., Klingmüller K., Pozzer A., Burnett R. T., Haines A., & Ramanathan V. (2019) *Effects of fossil fuel and total anthropogenic emission removal on public health and climate*, PROC. NAT'L. ACAD. SCI. 116(15): 7192–7197, 7194 ("Finally, our model simulations show that fossil-fuel-related aerosols have masked about 0.51(±0.03) °C of the global warming from increasing greenhouse gases (Fig. 3). The largest temperature impacts are found over North America and Northeast Asia, being up to 2 °C. By removing all anthropogenic emissions, a mean global temperature increase of 0.73(±0.03) °C could even warm some regions up to 3 °C. Since the temperature increase from past CO_2 emissions is irreversible on human timescales, the aerosol warming will be unleashed during the phaseout (11, 19–22)."). *See also* Intergovernmental Panel on Climate Change (2021) *Summary for Policymakers*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), SPM-2 (Figure SPM.2c shows that Sulphur dioxide (SO_2) contributes –0.49 °C (–0.10 to –0.93 °C) to observed warming in 2010–2019 relative to 1850–1900); Samset B. H., Sand M., Smith C. J., Bauer S. E., Forster P. M., Fuglestvedt J. S., Osprey S., & Schleussner C.-F. (2018) *Climate impacts from a removal of anthropogenic aerosol emissions*, GEOPHYS. RES. LETT. 45(2): 1020–1029, 1020 ("Limiting global warming to 1.5 or 2.0°C requires strong mitigation of anthropogenic greenhouse gas (GHG) emissions. Concurrently, emissions of anthropogenic aerosols will decline, due to coemission with GHG, and measures to improve air quality. … Removing aerosols induces a global mean surface heating of 0.5–1.1°C, and precipitation increase of 2.0–4.6%. Extreme weather indices also increase. We find a higher sensitivity of extreme events to aerosol reductions, per degree of surface warming, in particular over the major aerosol emission regions. … "Plain Language Summary. To keep within 1.5 or 2° of global warming, we need massive reductions of greenhouse gas emissions. At the same time, aerosol emissions will be strongly reduced. We show how cleaning up aerosols, predominantly sulfate, may add an additional half a degree of global warming, with impacts that strengthen those from greenhouse gas warming. The northern hemisphere is found to be more sensitive to aerosol removal than greenhouse gas warming, because of where the aerosols are emitted today. This means that it does not only matter whether or not we reach international climate targets. It also matters how we get there."); *and* Feijoo F., Mignone B. K., Kheshgi H. S., Hartin C., McJeon H., & Edmonds J. (2019) *Climate and carbon budget implications of linked future changes in CO_2 and non-CO_2 forcing*, ENVIRON. RES. LETT. 14(4):04407, 1–11.

[134] Bodansky D. & Pomerance R. (2021) *Sustaining the Arctic in Order to Sustain the Global Climate System*, SUSTAINABILITY 13(19): 10622, 1 ("Volcanic eruptions provide proof-of-concept that stratospheric aerosols cool the planet. The sulfur aerosols injected into the stratosphere by the eruption of Mount Pinatubo in 1991 cooled the planet by about 0.5 °C."). *See also* NASA Earth Observatory (2001) *Global Effects of Mount Pinatubo* ("Pinatubo injected about 15 million tons of sulfur dioxide into the stratosphere, where it reacted with water to form a hazy layer of aerosol particles composed primarily of sulfuric acid droplets. Over the course of the next two years strong stratospheric winds spread these aerosol particles around the globe…. In the case of Mount Pinatubo, the result was a measurable cooling of the Earth's surface for a period of almost two years. Because they scatter and absorb incoming sunlight, aerosol particles exert a cooling effect on the Earth's surface. The Pinatubo eruption increased aerosol optical depth in the

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stratosphere by a factor of 10 to 100 times normal levels measured prior to the eruption. ("Aerosol optical depth" is a measure of how much light airborne particles prevent from passing through a column of atmosphere.) Consequently, over the next 15 months, scientists measured a drop in the average global temperature of about 1 degree F (0.6 degrees C)."); *and* Dutton E. G. & Christy J. R. (1992) *Solar radiative forcing at selected locations and evidence for global lower tropospheric cooling following the eruptions of El Chichón and Pinatubo*, Geophys. Res. Lett. 19(23): 2313–2316, 2313 ("By September 1992 the global and northern hemispheric lower tropospheric temperatures had decreased 0.5°C and 0.7°C, respectively compared to pre-Pinatubo levels.").

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

[136] Xu Y. & Ramanathan V. (2017) *Well below 2 °C: Mitigation strategies for avoiding dangerous to catastrophic climate changes*, Proc. Nat'l. Acad. Sci. 114(39): 10315–10323, 10320, Table S1 ("Hence, the CO_2 measures implemented in 2020 will unmask some of the aerosol cooling (red lines in SI Appendix, Fig. S5) and offset the warming reduction by CO_2 and SLCP mitigation. In the baseline scenarios of this study, the cooling aerosols are regulated gradually between 2020 and 2100 (SI Appendix, Fig. S6), whereas in the mitigation scenario examined here, CO_2 mitigation is implemented starting from 2020 and CO_2 emission is brought to net zero in about three decades (SI Appendix, Fig. S2B). As a result, the unmasking of coemitted aerosol cooling (a net warming effect) is more rapid in the decreasing CO_2 emissions beginning in 2020 (CN2020) mitigation scenario (SI Appendix, Fig. S5B vs. S7)."; Table S1 [graph depicting warming potential based on cumulative emissions from CO_2 only, aerosols only, and short-lived climate pollutants only from the 1970's into the 2090's]). *See also* Xu Y. (2020, personal communication). The baseline-fast warming scenario against which these mitigation scenarios are compared includes "unmasking" as emissions of cooling aerosols are reduced in the baseline-fast (RCP6.0) scenarios. If these aerosol emissions continued at current emission levels, undesired from air quality perspective, the warming in 2100 would be 0.6°C smaller.

[137] Xu Y. & Ramanathan V. (2017) *Well below 2 ºC: Mitigation strategies for avoiding dangerous to catastrophic climate changes*, Proc. Nat'l. Acad. Sci. 114(39): 10315–10323, Supplemental Information, 1 ("In the Baseline-default scenario for CO_2, the emission keeps increasing throughout the 21st century (RCP8.5). The 5% to 95% range of baseline-default is also adopted (Fig. S1b). In the baseline-fast scenario for CO_2 (pre-INDCs), emissions effectively increase at a rate of 1.1%/year before 2030 and then following Representative Concentration Pathway 6.0 (Fig. S1a). In the mitigation scenario for CO_2 (i.e. INDCs and post-2030 decarbonization), emissions effectively increase at a rate of 0.8%/year before 2030 (following INDCs) and then decrease at a rate of 5.5%/year after 2030 (CN2030 in Fig. S2a).").

[138] Xu Y. & Ramanathan V. (2017) *Well below 2 ºC: Mitigation strategies for avoiding dangerous to catastrophic climate changes*, Proc. Nat'l. Acad. Sci. 114(39): 10315–10323, Supplemental Information, 1 ("In the Baseline-default scenario for CO_2, the emission keeps increasing throughout the 21st century (RCP8.5). The 5% to 95% range of baseline-default is also adopted (Fig. S1b). In the baseline-fast scenario for CO_2 (pre-INDCs), emissions effectively increase at a rate of 1.1%/year before 2030 and then following Representative Concentration Pathway 6.0 (Fig. S1a). In the mitigation scenario for CO_2 (i.e. INDCs and post-2030 decarbonization), emissions effectively increase at a rate of 0.8%/year before 2030 (following INDCs) and then decrease at a rate of 5.5%/year after 2030 (CN2030 in Fig. S2a). The CN2020 scenario is the same as CN2030, except that the peak of emission is reached at 2020 (Fig. S2b)."). *See also Id.* Supplemental Information, 7 (Table S1. The contribution of individual mitigation measures to the warming in the 21st century.).

[139] 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, 408–411, Addendum "Methods" ("These results differ greatly from the idealized picture of a near-instantaneous response to the removal of aerosol cooling followed by a slow transition to dominance by the effects of CO_2. In these more plausible cases, the temperature effects of the reduction in CO_2, SO_2 and CH_4 roughly balance one another until about 2035. After this, the cooling effects of reduced CO_2 continue to increase, whereas the warming induced by a reduction in SO_2 and the cooling induced by the reduction in CH_4 taper off, such that the cooling induced by the reduction in CO_2 dominates (Fig. 3). Examining the effects of CO_2 and SO_2 alone (Fig. 3d), the faster response of SO_2 to the changes in emissions means that the net effect of these two pollutants would indeed be a short-term warming—but a very small one, of between 0.02 °C and 0.10 °C in the ensemble mean temperature response (up to 0.30 °C for the 95th percentile across pathways). Accounting for all fossil-related emissions (Fig. 3e), any brief

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climate penalty decreases to no more than 0.05 °C (0.19 °C at the 95th percentile), with the smaller value largely due to the additional near-term cooling from reductions in methane. Nearly all the warming in the 2020s and 2030s (Fig. 2) is therefore attributable to the effect of the residual emissions (mainly of CO_2) during the gradual fossil phase-out, as well as the response to historical emissions."; "We note that, although this study focuses on the effects of fossil-fuel related emissions, accounting for the effects of reductions in greenhouse gases from non-fossil sources—including fluorinated gases and both methane and nitrous oxide from agriculture—along with biofuels that are a large source of warming black carbon, could eliminate any near-term penalty entirely. In fact, given that the net effect of the fossil-fuel phase-out on temperature is minimal during the first 20 years (Fig. 3), reducing those other emissions is the only plausible way in which to decrease warming during that period."). *See also* Lelieveld J., Klingmüller K., Pozzer A., Burnett R. T., Haines A., & Ramanathan V. (2019) *Effects of fossil fuel and total anthropogenic emission removal on public health and climate*, PROC. NAT'L. ACAD. SCI. 116(15): 7192–7197, 7194 ("Some near-term mitigation can be achieved from the simultaneous reduction of short-lived greenhouse gases such as methane (CH_4), O_3, and hydrofluorocarbons (HFCs) (15, 23–25). Fossil-fuel-related CH_4 emissions constitute nearly 20% of the total source, and removing all anthropogenic CH_4 (nearly 60% of the source), in addition to anthropogenic O_3, would limit the near-term warming to 0.36(±0.06) °C. While the current climate forcing of HFCs is still small, it will be critical to prevent increases in the future, as they are potent greenhouse gases (26). Table 1 presents the unavoidable net warming from emission control measures that simultaneously affect aerosols and greenhouse gases, which have many sources in common. SI Appendix, Table S1 lists these results for all countries, including the uncertainty intervals.").

[140] Naik V., *et al.* (2021) *Chapter 6: Short-lived climate forcers*, in CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 6-7, 6-8 ("Across the SSPs, the collective reduction of CH_4, ozone precursors and HFCs can make a difference of global mean surface air temperature of 0.2 with a very likely range of [0.1–0.4] °C in 2040 and 0.8 with a very likely range of [0.5–1.3] °C at the end of the 21st century (comparing SSP3-7.0 and SSP1-1.9), which is substantial in the context of the Paris Agreement. Sustained methane mitigation, wherever it occurs, stands out as an option that combines near- and long-term gains on surface temperature (*high confidence*) and leads to air quality benefits by reducing surface ozone levels globally (*high confidence*). {6.6.3, 6.7.3, 4.4.4}"; "Additional CH_4 and BC mitigation would contribute to offsetting the additional warming associated with SO_2 reductions that would accompany decarbonization (*high confidence*).").

[141] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS, 21 ("This is because a realistically paced phase-out of fossil fuels, or even a rapid one under aggressive decarbonization, is likely to have minimal net impacts on near-term temperatures due to the removal of co-emitted aerosols (Shindell and Smith 2019). As methane is the most powerful driver of climate change among the short-lived substances (Myhre et al. 2013), mitigation of methane emissions is very likely to be the most powerful lever in reducing near-term warming. This is consistent with other assessments; for example, the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5) showed that methane controls implemented between 2010 and 2030 would lead to a larger reduction in 2040 warming than the difference between RCPs 2.6, 4.5 and 6.0 scenarios. (The noted IPCC AR5-era scenarios are called representative concentration pathways (RCPs, with the numerical value indicating the target radiative forcing in 2100 (Kirtman et al. 2013))."). *See also* Shindell D. & Smith C. J. (2019) *Climate and air-quality benefits of a realistic phase-out of fossil fuels*, NATURE 573: 408–411, Addendum "Methods" ("We note that, although this study focuses on the effects of fossil-fuel related emissions, accounting for the effects of reductions in greenhouse gases from non-fossil sources—including fluorinated gases and both methane and nitrous oxide from agriculture—along with biofuels that are a large source of warming black carbon, could eliminate any near-term penalty entirely. In fact, given that the net effect of the fossil-fuel phase-out on temperature is minimal during the first 20 years (Fig. 3), reducing those other emissions is the only plausible way in which to decrease warming during that period.").

[142] Dreyfus G. B., Xu Y., Shindell D. T., Zaelke D., & Ramanathan V. (2022) *Mitigation climate disruption in time: A self-consistent approach for avoiding both near-term and long-term global warming*, PROC. NAT'L. ACAD. SCI. (*in press*) ("Aggressive decarbonization to achieve net-zero CO_2 emissions in the 2050s (as in the decarb-only scenario) results in weakly accelerated net warming compared to the reference case, with a positive warming up to 0.03 °C in the mid-2030s, and no net avoided warming until the mid-2040s due to the reduction in co-emitted cooling aerosols (Figure 3a). By 2050, decarbonization measures result in very limited net avoided warming (0.07°C), consistent with Shindell and Smith (43), but rise to a likely detectable 0.25°C by 2060 and a major benefit of 1.4°C by 2100 (Table S5). In contrast, pairing decarbonization with mitigation measures targeting CH_4, BC, HFC, and N_2O (not an SLCP

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due to its longer lifetime) independent from decarbonization are essential to slowing the rate of warming by the 2030s to under 0.3°C per decade (Table 1, Figure 3b), similar to the 0.2°C to 0.25°C per decade warming prior to 2020 (38, 53). Recent studies suggest that rate of warming rather than level of warming controls likelihood of record-shattering extreme weather events (54, 55). By 2050, the net avoided warming from the targeted non-CO_2 measures is 0.26°C, almost 4 times larger than the net benefit of decarbonization alone (0.07°C) (Table S5).").

[143] Xu Y. & Ramanathan V. (2017) *Well below 2 °C: Mitigation strategies for avoiding dangerous to catastrophic climate changes*, PROC. NAT'L. ACAD. SCI. 114(39): 10315–10323, 10321 ("The SP [super pollutant] lever targets SLCPs. Reducing SLCP emissions thins the SP blanket within few decades, given the shorter lifetimes of SLCPs (weeks for BC to about 15 years for HFCs). The mitigation potential of the SP lever with a maximum deployment of current technologies … is about 0.6 °C by 2050 and 1.2 °C by 2100 (SI Appendix, Fig. S5B and Table S1)."). *See also* Naik V., *et al.* (2021) *Chapter 6: Short-lived climate forcers*, in CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 6-7 ("Across the SSPs, the collective reduction of CH_4, ozone precursors and HFCs can make a difference of global mean surface air temperature of 0.2 with a very likely range of [0.1–0.4] °C in 2040 and 0.8 with a very likely range of [0.5–1.3] °C at the end of the 21st century (comparing SSP3-7.0 and SSP1-1.9), which is substantial in the context of the Paris Agreement. Sustained methane mitigation, wherever it occurs, stands out as an option that combines near- and long-term gains on surface temperature (*high confidence*) and leads to air quality benefits by reducing surface ozone levels globally (*high confidence*). {6.6.3, 6.7.3, 4.4.4}").

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

[145] Intergovernmental Panel on Climate Change (2022) *Summary for Policymakers*, *in* CLIMATE CHANGE 2022: MITIGATION OF CLIMATE CHANGE, *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Shukla P. R., *et al.* (eds.), SPM-22 ("C.1.2 In modelled pathways that limit warming to 2°C (>67%) assuming immediate action, global net CO_2 emissions are reduced compared to modelled 2019 emissions by 27% [11–46%] in 2030 and by 52% [36-70%] in 2040; and global CH_4 emissions are reduced by 24% [9–53%] in 2030 and by 37% [20–60%] in 2040. In pathways that limit warming to 1.5°C (>50%) with no or limited overshoot global net CO_2 emissions are reduced compared to modelled 2019 emissions by 48% [36–69%] in 2030 and by 80% [61-109%] in 2040; and global CH_4 emissions are reduced by 34% [21–57%] in 2030 and 44% [31-63%] in 2040. There are similar reductions of non-CO_2 emissions by 2050 in both types of pathways: CH_4 is reduced by 45% [25–70%]; N_2O is reduced by 20% [-5 – 55%]; and F-Gases are reduced by 85% [20–90%]. [FOOTNOTE 44] Across most modelled pathways, this is the maximum technical potential for anthropogenic CH_4 reductions in the

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underlying models (*high confidence*). Further emissions reductions, as illustrated by the IMP-SP pathway, may be achieved through changes in activity levels and/or technological innovations beyond those represented in the majority of the pathways (*medium confidence*). Higher emissions reductions of CH_4 could further reduce peak warming. (*high confidence*) (Figure SPM.5) {3.3}").

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

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

[148] Ripple W. J., Wolf C., Newsome T. M., Barnard P., & Moomaw W. R. (2019) *World Scientists' Warning of a Climate Emergency*, BioScience 70: 8–12.

[149] Ripple W. J., Wolf C., Newsome T. M., Gregg J. W., Lenton T. M., Palomo I., Eikelboom J. A. J., Law B. E., Huq S., Duffy P. B., & Rockström J. (2021) *World Scientists' Warning of a Climate Emergency 2021*, BioScience: biab079, 1–5, 4 ("Given the impacts we are seeing at roughly 1.25 degrees Celsius (°C) warming, combined with the many reinforcing feedback loops and potential tipping points, massive-scale climate action is urgently needed. The remaining carbon budget for 1.5°C was recently estimated to have a 17% chance of being negative, indicating that we may already have lost the opportunity to limit warming to this level without overshoot or risky geoengineering (Matthews et al. 2021). Because of the limited time available, priorities must shift toward immediate and drastic reductions in dangerous short-lived greenhouse gases, especially methane (UNEP/CCAC 2021).").

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

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

[152] (8 November 2021) *LIVE: President Obama delivers a speech at COP26 climate summit in Glasgow, Scotland*, Yahoo Finance, Youtube (from 23:12–23:19).

[153] United Nations Environment Programme & Climate & Clean Air Coalition (2021) Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions, 17 ("Mitigation of methane is very likely

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the strategy with the greatest potential to decrease warming over the next 20 years."). *See also* Ross K., Waskow D., & Ge M. (17 September 2021) *How Methane Emissions Contribute to Climate Change*, WORLD RESOURCES INSTITUTE.

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

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

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

[157] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS, 21 ("This is because a realistically paced phase-out of fossil fuels, or even a rapid one under aggressive decarbonization, is likely to have minimal net impacts on near-term temperatures due to the removal of co-emitted aerosols (Shindell and Smith 2019). As methane is the most powerful driver of climate change among the short-lived substances (Myhre et al. 2013), mitigation of methane emissions is very likely to be the most powerful lever in reducing near-term warming. This is consistent with other assessments; for example, the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5) showed that methane controls implemented between 2010 and 2030 would lead to a larger reduction in 2040 warming than the difference between RCPs 2.6, 4.5 and 6.0 scenarios. (The noted IPCC AR5-era scenarios are called representative concentration pathways (RCPs, with the numerical value indicating the target radiative forcing in 2100 (Kirtman et al. 2013))."). *See also* Ocko I. B., Sun T., Shindell D., Oppenheimer M., Hristov A. N., Pacala S.W., Mauzerall D. L., Xu Y., & Hamburg S. P. (2021) *Acting rapidly to deploy readily available methane mitigation measures by sector can immediately slow global warming*, ENVIRON. RES. LETT. 16(5): 054042 ("Pursuing all mitigation measures now could slow the global-mean rate of near-term decadal warming by around 30%, avoid a quarter of a degree centigrade of additional global-mean warming by midcentury, and set ourselves on a path to avoid more than half a degree centigrade by end of century. On the other hand, slow implementation of these measures may result in an additional tenth of a degree of global-mean warming by midcentury and 5% faster warming rate (relative to fast action), and waiting to pursue these measures until midcentury may result in an additional two tenths of a degree centigrade by midcentury and 15% faster warming rate (relative to fast action).").

[158] United Nations Environment Programme & World Meteorological Organization (2011) INTEGRATED ASSESSMENT OF BLACK CARBON AND TROPOSPHERIC OZONE, 254 ("Evaluating global mean temperature change, it was found that the targeted measures to reduce emissions of methane and BC could greatly reduce warming rates over the next few decades (Figure 6.1; Box 6.1). When all measures are fully implemented, warming during the 2030s relative to the

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present would be only half as much as in the reference scenario. In contrast, even a fairly aggressive strategy to reduce CO_2 emissions, as for the CO_2-measures scenario, does little to mitigate warming until after the next 20-30 years (Box 6.2).”); 262 (“Large impacts of the measures examined here were also seen for the Arctic despite the minimal amount of emissions currently taking place there. This occurs due to the high sensitivity of the Arctic both to pollutants that are transported there from remote sources and to radiative forcing that takes place in areas of the northern hemisphere outside the Arctic. The 16 measures examined here, including the measures on pellet stoves and coal briquettes, reduce warming in the Arctic by 0.7 ºC (range 0.2 to 1.3 ºC) at 2040. This is a large portion of the 1.1 ºC (range 0.7 to 1.7 ºC) warming projected under the reference scenario for the Arctic, and hence implementation of the measures would be virtually certain to substantially slow, but not halt, the pace of Arctic climate change.”).

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

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

[161] Intergovernmental Panel on Climate Change (2022) *Summary for Policymakers*, *in* CLIMATE CHANGE 2022: MITIGATION OF CLIMATE CHANGE, *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Shukla P. R., *et al.* (eds.), SPM-30–SPM-31 (“Deep GHG emissions reductions by 2030 and 2040, particularly reductions of methane emissions, lower peak warming, reduce the likelihood of overshooting warming limits and lead to less reliance on net negative CO2 emissions that reverse warming in the latter half of the century. Reaching and sustaining global net zero GHG emissions results in a gradual decline in warming. (high confidence) (Table SPM.1) {3.3, 3.5, Box 3.4, Cross-Chapter Box 3 in Chapter 3, AR6 WG I SPM D1.8}”).

[162] Intergovernmental Panel on Climate Change (2022) *Summary for Policymakers*, *in* CLIMATE CHANGE 2022: MITIGATION OF CLIMATE CHANGE, *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Shukla P. R., *et al.* (eds.), SPM-22 (“C.1.2 In modelled pathways that limit warming to 2°C (>67%) assuming immediate action, global net CO2 emissions are reduced compared to modelled 2019 emissions by 27% [11–46%] in 2030 and by 52% [36-70%] in 2040; and global CH4 emissions are reduced by 24% [9–53%] in 2030 and by 37% [20–60%] in 2040. In pathways that limit warming to 1.5°C (>50%) with no or limited overshoot global net CO2 emissions are reduced compared to modelled 2019 emissions by 48% [36–69%] in 2030 and by 80% [61-109%] in 2040; and global CH4 emissions are reduced by 34% [21–57%] in 2030 and 44% [31-63%] in 2040. There are similar reductions of non-CO2 emissions by 2050 in both types of pathways: CH4 is reduced by 45% [25–70%]; N2O is reduced by 20% [-5 – 55%]; and F-Gases are reduced by 85% [20–90%]. [FOOTNOTE 44] Across most modelled pathways, this is the maximum technical potential for anthropogenic CH4 reductions in the underlying models (high confidence). Further emissions reductions, as illustrated by the IMP-SP pathway, may be achieved through changes in activity levels and/or technological innovations beyond those represented in the majority of the pathways (medium confidence). Higher emissions reductions of CH4 could further reduce peak warming. (high confidence) (Figure SPM.5) {3.3}”).

[163] Saunois M., *et al*. (2020) *The Global Methane Budget* 2000-2017, EARTH SYST. SCI. DATA 12(3): 1561–1623, 1561 (“For the 2008–2017 decade, global methane emissions are estimated by atmospheric inversions (a top-down approach) to be 576 Tg CH4 yr−1 (range 550–594, corresponding to the minimum and maximum estimates of the model ensemble). Of this total, 359 Tg CH4 yr−1 or ∼ 60 % is attributed to anthropogenic sources, that is emissions caused by direct human activity (i.e. anthropogenic emissions; range 336–376 Tg CH4 yr−1 or 50 %–65 %).”).

[164] United Nations Environment Programme & Climate & Clean Air Coalition (2021) GLOBAL METHANE ASSESSMENT: BENEFITS AND COSTS OF MITIGATING METHANE EMISSIONS, 25 (“Anthropogenic methane emissions come primarily from three sectors: fossil fuels, ~35 per cent; agriculture, ~40 per cent; and waste, ~20 per cent.”).

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

[166] Jackson R. B., *et al.* (2020) *Increasing anthropogenic methane emissions arise equally from agricultural and fossil fuel sources*, ENVIRON. RES. LETT. 15(071002): 1–7, 6 ("Increased emissions from both the agriculture and waste sector and the fossil fuel sector are likely the dominant cause of this global increase (figures 1 and 4), highlighting the need for stronger mitigation in both areas. Our analysis also highlights emission increases in agriculture, waste, and fossil fuel sectors from southern and southeastern Asia, including China, as well as increases in the fossil fuel sector in the United States (figure 4). In contrast, Europe is the only continent in which methane emissions appear to be decreasing. While changes in the sink of methane from atmospheric or soil uptake remains possible (Turner *et al* 2019), atmospheric chemistry and land-surface models suggest the timescales for sink responses are too slow to explain most of the increased methane in the atmosphere in recent years. Climate policies overall, where present for methane mitigation, have yet to alter substantially the global emissions trajectory to date.").

[167] Clean Air Task Force, 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.").

[168] Clean Air Task Force, 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.").

[169] Clean Air Task Force, 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.").

[170] Clean Air Task Force, 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* 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.").

[171] United States Climate Alliance (2018) FROM SLCP CHALLENGE TO ACTION: A ROADMAP FOR REDUCING SHORT-LIVED CLIMATE POLLUTANTS TO MEET THE GOALS OF THE PARIS AGREEMENT, 13 ("Actions to improve manure management and to reduce methane from enteric fermentation have the potential to significantly reduce agricultural methane emissions across U.S. Climate Alliance states. Improving manure storage and handling, composting manure, utilizing pasture-based systems, or installing anaerobic digesters significantly reduces methane from manure management on dairy, swine, and other livestock operations. These practices may reduce methane from manure management by as much as 70 percent in U.S. Climate Alliance states (Appendix A) and can help improve soil quality and fertility, reduce water use and increase water quality, reduce odors, and decrease the need for synthetic fertilizers and associated greenhouse gas emissions. Promising technologies are also emerging that may cut methane emissions from enteric fermentation by 30 percent or more (Appendix A). Developing strategies that work for farmers and surrounding communities can significantly reduce methane emissions, increase and diversify farm revenues, and support water quality and other environmental benefits."). *See also* Höglund-Isaksson L., Gómez-Sanabria A., Klimont Z., Rafaj P., & Schöpp W. (2020) *Technical potentials and costs for reducing global anthropogenic methane emissions in the 2050 timeframe—results from the GAINS model*, ENVIRON. RES. COMM. 2(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 CH4 emissions from livestock and for this group we find it technically feasible to reduce emissions by just over 30 percent below baseline emissions in year 2050 (see figures S6–2 in the SI). The available options include reduction of enteric fermentation emissions through animal feed changes (Gerberetal 2013, Hristov et al 2013) combined with implementation of breeding schemes that simultaneously target genetic traits for improved productivity and enhanced animal health/longevity and fertility. Increased productivity reduces system emissions by enabling the production of the same amount of milk using fewer animals. The dual objective in breeding schemes is important as a one-eyed focus on increased productivity leads to deteriorating animal health and fertility and a risk that system emissions increase due to a need to keep a larger fraction of unproductive replacement animals in the stock (Lovett et al 2006, Berglund 2008, Bell et al 2011). The enteric fermentation options are considered economically feasible for commercial/industrial farms with more than 100 LSU but not for smaller- and medium- sized farms. Breeding schemes are assumed to deliver impacts on emissions only after 20 years and feed changes are assumed applicable only while animals are housed indoor. Emissions from manure management can be reduced through treatment of manure in anaerobic digesters (ADs) with biogas recovery. To be efficient from both an economic and environmental point of view, a certain scale is needed to accommodate both the fixed investment of the AD plant and the time farmers spend carefully attending to and maintaining the process (for details see section 3.3.1.3 in Höglund-Isaksson et al 2018).") *and* Borgonovo F., *et al.* (2019) *Improving the sustainability of dairy slurry with a commercial additive treatment*, SUSTAINABILITY 11(4988): 1–14, 8 ("N_2O, CO_2, and CH_4 emissions, from the treated slurry, were respectively 100%, 22.9% and 21.5% lower than the control at T4 when the emission peaks were recorded.").

[172] Höglund-Isaksson L., Gómez-Sanabria A., Zbigniew K., Rafaj P., & Schöpp W. (2020) *Technical potentials and costs for reducing global anthropogenic methane emissions in the 2050 timeframe—results from the GAINS model*, ENVIRON. RES. COMM. 2(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_2eq 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.").

[173] 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

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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.”).

[174] Jackson R. B., *et al.* (2021) *Atmospheric methane removal: a research agenda*, PHILOS. TRANS. R. SOC. A 379: 1–17, 1 (“Atmospheric methane removal may be needed to offset continued methane release and limit the global warming contribution of this potent greenhouse gas. Eliminating most anthropogenic methane emissions is unlikely this century, and sudden methane release from the Arctic or elsewhere cannot be excluded, so technologies for negative emissions of methane may be needed. Carbon dioxide removal (CDR) has a well-established research agenda, technological foundation and comparative modelling framework [23–28]. No such framework exists for methane removal. We outline considerations for such an agenda here. We start by presenting the technological Mt CH4 yr–1 considerations for methane removal: energy requirements (§2a), specific proposed technologies (§2b), and air processing and scaling requirements (§2c). We then outline the climate and air quality impacts and feedbacks of methane removal (§3a) and argue for the creation of a Methane Removal Model Intercomparison Project (§3b), a multi-model framework that would better quantify the expected impacts of methane removal. In §4, we discuss some broader implications of methane removal.”). *See also* Abernethy S., O’Connor F. M., Jones C. D., & Jackson R. B. (2021) *Methane removal and the proportional reductions in surface temperature and ozone*, PHILOS. TRANS. R. SOC. A 379: 1–13, 6 (“Due to the temporal nature of effective cumulative removal, comparisons between methane and carbon dioxide depend on the timescale of interest. The equivalent of MCR for carbon dioxide, the TCRE, is 0.00048 ± 0.0001°C per Pg CO_2 [38], two orders of magnitude smaller than our MCR estimate of 0.21 ± 0.04°C per effective Pg CH_4 removed (figure 2). Accounting for the time delay for carbon dioxide removal due to the lagged response of the deep ocean, the TCRE for CO2 removal may be even lower [39]. If 1 year of anthropogenic emissions was removed (0.36 Pg CH_4 [3] and 41.4 Pg CO_2 [40]), the transient temperature impact would be almost four times larger for methane than for CO_2 (0.075°C compared to 0.02°C). Using this example, however, maintaining a steady-state response of 0.36 Pg CH_4 effectively removed would require the ongoing removal of roughly 0.03Pg CH_4 yr−1, since a removal rate of E/τ is required to maintain an effective cumulative removal of *E*.”).

[175] Saunois M., *et al.* (2020) *The Global Methane Budget 2000-2017*, EARTH SYST. SCI. DATA 12(3): 1561-1623 (“For the 2008–2017 decade, global methane emissions are estimated by atmospheric inversions (a top-down approach) to be 576 Tg CH4 yr−1 (range 550–594, corresponding to the minimum and maximum estimates of the model ensemble). Of this total, 359 Tg CH4 yr−1 or ∼ 60 % is attributed to anthropogenic sources, that is emissions caused by direct human activity (i.e. anthropogenic emissions; range 336–376 Tg CH4 yr−1 or 50 %–65 %).”).

[176] Abernethy S., O’Connor F. M., Jones C. D., & Jackson R. B. (2021) *Methane removal and the proportional reductions in surface temperature and ozone*, PHIL. TRANS. R. SOC. A 379: 1–13, 6 (“Due to the temporal nature of effective cumulative removal, comparisons between methane and carbon dioxide depend on the timescale of interest. The equivalent of MCR for carbon dioxide, the TCRE, is 0.00048 ± 0.0001°C per Pg CO_2 [38], two orders of magnitude smaller than our MCR estimate of 0.21 ± 0.04°C per effective Pg CH_4 removed (figure 2). Accounting for the time delay for carbon dioxide removal due to the lagged response of the deep ocean, the TCRE for CO2 removal may be even lower [39]. If 1 year of anthropogenic emissions was removed (0.36 Pg CH_4 [3] and 41.4 Pg CO_2 [40]), the transient temperature impact would be almost four times larger for methane than for CO_2 (0.075°C compared to 0.02°C). Using this example, however, maintaining a steady-state response of 0.36 Pg CH_4 effectively removed would require the ongoing removal of roughly 0.03 Pg CH_4 yr^{-1}, since a removal rate of E/τ is required to maintain an effective cumulative removal of *E*.”); *discussed in* Jordan R. (26 September 2021) *Stanford-led research reveals potential of an overlooked climate change solution*, STANFORD WOODS INSTITUTE FOR THE ENVIRONMENT (“The analyses, published Sept. 27 in Philosophical Transactions of the Royal Society A, reveal that removing about three years-worth of human caused emissions of the potent greenhouse gas would reduce global surface temperatures by approximately 0.21 degrees Celsius while reducing ozone levels enough to prevent roughly 50,000 premature deaths annually. The findings open the door to direct comparisons with carbon dioxide removal – an approach that has received significantly more research and investment – and could help shape national and international climate policy in the future. […] Under a high emissions scenario, the analysis showed that a 40 percent reduction in global methane emissions by 2050 would lead to a temperature reduction of approximately 0.4 degrees Celsius by 2050. Under a low emissions scenario where temperature peaks during the 21st century, methane removal of the same magnitude could reduce the peak temperature by up to 1 degree Celsius.”).

[177] O’Grady C. (2 November 2021) *To slow global warming, some researchers want to pull methane out of the air*, SCIENCE. (“At a side event at the summit, researchers with the advocacy group Methane Action argued that so-called

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negative emissions technologies—alongside every trick in the book to reduce emissions—could restore methane to pre-industrial levels and trim an estimated 0.4°C to 0.6°C of warming.”).

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

[179] White House (18 September 2021) *Joint US-EU Press Release on the Global Methane Pledge* (“At the Major Economies Forum on Energy and Climate (MEF) on September 17, 2021, President Biden and European Commission President Ursula von der Leyen announced, with support from seven additional countries, the Global Methane Pledge—an initiative to be launched at the World Leaders Summit at the 26th UN Climate Change Conference (COP-26) this November in Glasgow, United Kingdom.”).

[180] U.S. Department of State (2 November 2021) *United States, European Union, and Partners Formally Launch Global Methane Pledge to Keep 1.5°C Within Reach*, Press Release (“Today, the United States, the European Union, and partners formally launched the Global Methane Pledge, an initiative to reduce global methane emissions to keep the goal of limiting warming to 1.5 degrees Celsius within reach. A total of over 100 countries representing 70% of the global economy and nearly half of anthropogenic methane emissions have now signed onto the pledge.”). *See also* White House (18 September 2021) *Joint US-EU Press Release on the Global Methane Pledge*, Statements and Releases; *and* F. Harvey (17 September 2021) *US and EU pledge 30% cut in methane emissions to limit global heating*, THE GUARDIAN.

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

[182] U.S. Department of State (11 October 2021) *Joint U.S.-EU Statement on the Global Methane Pledge* (“Countries joining the Global Methane Pledge commit to a collective goal of reducing global methane emissions by at least 30 percent from 2020 levels by 2030 and moving towards using highest tier IPCC good practice inventory methodologies to quantify methane emissions, with a particular focus on high emission sources. Successful implementation of the Pledge would reduce warming by at least 0.2 degrees Celsius by 2050.”).

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

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

[185] 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.).

[186] Bond T. C., *et al.* (2013) *Bounding the role of black carbon in the climate system: A scientific assessment*, J. GEOPHYS. RES. ATMOS. 118(11): 5380–5552, 5420 (“Major sources of BC are also major sources of $PM_{2.5}$, but the converse is not always true; major sources of $PM_{2.5}$ may produce little BC if their emissions are primarily inorganic. Sources that are BC and OC emitters are shown in the table. Resuspended dust, secondary pollutants like sulfate and nitrate, or sea salt, could also be contributors to PM2.5 at some locations but are not included in Table 11.”); major

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sources in Table 11 include (in order of decreasing importance): transport (vehicle exhaust including gasoline and diesel); IN = industry including coal and oil and biomass burning; coal burning power plants; RE = residential energy; OB= open burning of biomass and refuse; SA = secondary aerosols; O= Others.

[187] Lelieveld J., Klingmüller K., Pozzer A., Burnett R. T., Haines A., & Ramanathan V. (2019) *Effects of fossil fuel and total anthropogenic emission removal on public health and climate*, Proc. Nat’l. Acad. Sci. 116(15): 7192–7197, 7193 (“We find that the global total excess mortality rate is 8.79 million per year, with a 95% confidence interval of 7.11–10.41 million per year.”). *See also* Vohra K., Vodonos A., Schwartz J., Marais E. A., Sulprizio M. P., & Mickley L. J. (2021) *Global mortality from outdoor fine particle pollution generated by fossil fuel combustion: Results from GEOS-Chem*, Environ. Res. 195: 110754 (“We used the chemical transport model GEOS-Chem to estimate global exposure levels to fossil-fuel related PM$_{2.5}$ in 2012. Relative risks of mortality were modeled using functions that link long-term exposure to PM$_{2.5}$ and mortality, incorporating nonlinearity in the concentration response. We estimate a global total of 10.2 (95% CI: -47.1 to 17.0) million premature deaths annually attributable to the fossil-fuel component of PM$_{2.5}$. The greatest mortality impact is estimated over regions with substantial fossil fuel related PM$_{2.5}$, notably China (3.9 million), India (2.5 million) and parts of eastern US, Europe and Southeast Asia. The estimate for China predates substantial decline in fossil fuel emissions and decreases to 2.4 million premature deaths due to 43.7% reduction in fossil fuel PM$_{2.5}$ from 2012 to 2018 bringing the global total to 8.7 (95% CI: -1.8 to 14.0) million premature deaths.”).

[188] Feng Z., Xu Y., Kobayashi K., Dai L., Zhang T., Agathokleous E., Calatayud V., Paoletti E., Mukherjee A., Agrawal M., Park R. J., Oak Y. J., & Yue X. (2022) *Ozone pollution threatens the production of major staple crops in East Asia*, Nat. Food 3: 47–56, 47 (“East Asia is a hotspot of surface ozone (O$_3$) pollution, which hinders crop growth and reduces yields. Here, we assess the relative yield loss in rice, wheat and maize due to O$_3$ by combining O$_3$ elevation experiments across Asia and air monitoring at about 3,000 locations in China, Japan and Korea. China shows the highest relative yield loss at 33%, 23% and 9% for wheat, rice and maize, respectively. The relative yield loss is much greater in hybrid than inbred rice, being close to that for wheat. Total O$_3$-induced annual loss of crop production is estimated at US$63 billion.”). *See also* United Nations Environment Programme & Climate & Clean Air Coalition (2021) Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions, 68 (“Methane also plays a significant role in reducing crop yields and the quality of vegetation. Ozone exposure is estimated to result in yield losses in wheat, 7.1 per cent; soybean,12.4 per cent; maize, 6.1 per cent; and rice, 4.4 per cent for near present-day global totals (Mills et al. 2018; Shindell et al. 2016; Avnery et al. 2011a)”); *and* Shindell D., Faluvegi G., Kasibhatla P., & Van Dingenen R. (2019) *Spatial Patterns of Crop Yield Change by Emitted Pollutant*, Earth’s Future 7(2): 101–112, 101 (“Our statistical modeling indicates that for the global mean, climate and composition changes have decreased wheat and maize yields substantially whereas rice yields have increased. Well-mixed greenhouse gasses drive most of the impacts, though aerosol-induced cooling can be important, particularly for more polluted area including India and China. Maize yield losses are most strongly attributable to methane emissions (via both temperature and ozone).”).

[189] United Nations Environment Programme & World Meteorological Organization (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone, 193, 201 (“Implementing all measures could avoid 2.4 million premature deaths (within a range of 0.7–4.6 million) associated with reductions in PM$_{2.5}$, associated with 5.3–37.4 million years of life lost (YLL), based on the 2030 population.”; “Total global production gains of all crops ranges between 30 and 140 million tonnes (model mean: 52 million tonnes). The annual economic gains for all four crops in all regions ranges between US$4billion and US$33 billion, of which US$2–28 billion in Asia.”).

[190] Climate & Clean Air Coalition, Black Carbon (*last visited* 8 February 2021) (Listing solutions to reach 70% reduction in black carbon by 2030).

[191] 1999 Protocol to Abate Acidification, Eutrophication and Ground-Level Ozone (Gothenburg Protocol), Decision 2012/8: Adoption of guidance document on control techniques for emissions of sulphur, nitrogen oxides, volatile organic compounds and particulate matter (including PM$_{10}$, PM$_{2.5}$, and black carbon) from stationary sources. *See also* Matthews B. & Paunu V.-V. (2019) *Review of Reporting Systems for National Black Carbon Emissions Inventories*, EU Action on Black Carbon in the Arctic - Technical Report 2, 1–2 (“Emissions reporting systems are thus in need of further improvement. In evaluating needs for improvement, the EU Action on Black Carbon in the Arctic review identified the following priority areas . . . 4. Enhanced cooperation between CLRTAP and the Arctic Council to expand and harmonise black carbon emissions reporting by countries whose black carbon emissions impact the Arctic.”).

Compare with Expert Group on Black Carbon and Methane (2019) *Summary of Progress and Recommendations*, Arctic Council Secretartiat, 32, Table 5 (Showing US with 9.5bcm of flaring based on World Bank satellite observations); *with* Energy Information Administration, Flaring and Venting Data (*last visited* 5 February 2021) (showing combined flaring and venting volumes of 255bcf for 2017).

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

[193] Clean Air Task Force, 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."); *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.").

[194] International Energy Agency, International Renewable Energy Agency, United Nations Statistics Division, World Bank, & World Health Organization (2020) TRACKING SDG 7: THE ENERGY PROGRESS REPORT, 6 ("The share of the global population with access to clean fuels and technologies for cooking increased from 56 percent in 2010 (uncertainty interval 52–61 percent) to 63 percent in 2018 (56–68), leaving approximately 2.8 billion people without access.[1] That number has been largely unchanged over the past two decades owing to population growth outpacing the number of people gaining access to clean cooking solutions."). Cleaner cookstoves must also be reliable for internvetions to succeed. *See* Ramanathan T., Molin Valdés H., & Coldrey O. (7 September 2020) *Reliability matters:*

Achieving affordable, reliable, sustainable and modern energy for all by 2030, SUSTAINABLE ENERGY FOR ALL ("A cooking solution (improved biomass, gas, electric, etc.) is reliable when it offers a household the predictable ability to cleanly cook essential foods on a daily basis and to continue to do so into the foreseeable future. Reliability is a holistic concept that encompasses not only the verifiability of emissions reduction, but also accounts for end users' needs (e.g. usability of design, long-term durability, affordability, and strength of supply chain). Compromising any of those factors can mean that even if a cooking solution is perceived as beneficial, it may not be well suited and will therefore ultimately not meet its targeted goal of cleaner air.").

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

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

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

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

[198] International Maritime Organization, Marine Environment Protection Committee (MEPC 76), 10 to 17 June 2021 (remote session) (*last visited* 13 October 2021) ("The MEPC adopted amendments to MARPOL Annex I (addition of a new regulation 43A) to introduce a prohibition on the use and carriage for use as fuel of heavy fuel oil (HFO) by ships in Arctic waters on and after 1 July 2024. The prohibition will cover the use and carriage for use as fuel of oils having a density at 15°C higher than 900 kg/m3 or a kinematic viscosity at 50°C higher than 180 mm2/s. Ships engaged in securing the safety of ships, or in search and rescue operations, and ships dedicated to oil spill preparedness and response would be exempted. Ships which meet certain construction standards with regard to oil fuel tank protection would need to comply on and after 1 July 2029. A Party to MARPOL with a coastline bordering Arctic waters may temporarily waive the requirements for ships flying its flag while operating in waters subject to that Party's sovereignty or jurisdiction, up to 1 July 2029.").

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

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

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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.”).

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

[202] Arctic Council (2019) Expert Group on Black Carbon and Methane Summary Of Progress And Recommendations 2019, Summary Report.

[203] Organisation for Economic Co-operation and Development (April 2021) *Executive Summary*, *in* The Economic Benefits of Air Quality Improvements in Arctic Council Countries, OECD report.

[204] Organisation for Economic Co-operation and Development (April 2021) *Chapter 3: Air quality improvements and health benefits of air pollution policies*, *in* The Economic Benefits of Air Quality Improvements in Arctic Council Countries, OECD report.

[205] International Maritime Organization (1 December 2021) *IMO moves ahead on GHG emissions, Black Carbon and marine litter*, News (“The International Maritime Organization (IMO) in view of the urgency for all sectors to accelerate their efforts to reduce GHG emissions - as emphasized in the recent IPCC reports and the Glasgow Climate Pact - recognized the need to strengthen the ambition of the Initial IMO GHG Strategy during its revision process. IMO's Marine Environment Protection Committee (MEPC), meeting virtually for its 77th session, 22-26 November 2021, agreed to initiate the revision of its GHG strategy. The MEPC also adopted a resolution on voluntary use of cleaner fuels in the Arctic, to reduce black carbon emissions. In other work, the MEPC adopted a strategy to address marine plastic litter from ships; adopted revised guidelines for exhaust gas cleaning systems (EGCS) and agreed the scope of work on discharge water of EGCS; and considered matters related to the Ballast Water Management Convention.”). *See also* Humpert M. (6 December 2021) *IMO adopts new measures to reduce black carbon in Arctic shipping*, ArcticToday.

[206] Guzman J. (1 December 2020) *Every major US bank has now come out against Arctic drilling*, The Hill.

[207] Fountain H. (6 January 2021) *Sale of Drilling Leases in Arctic Refuge Fails to Yield a Windfall*, New York Times.

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

[209] Velders G. J. M., Andersen S. O., Daniel J. S., Fahey D. W., & McFarland M. (2007) *The importance of the Montreal Protocol in protecting climate*, Proc. Nat. Acad. Sci. 104(12): 4814–4819, 4816 (“In contrast, without the early warning of the effects of CFCs (MR74 scenario), estimated ODS emissions would have reached 24–76 GtCO$_2$-eq yr 1 in 2010. Thus, in the current decade, in a world without ODS restrictions, annual ODS emissions using only the GWP metric could be as important for climate forcing as those of CO$_2$.”).

[210] Young P. J., Harper A. B., Huntingford C., Paul N. D., Morgenstern O., Newman P. A., Oman L. D., Madronich S., & Garcia R. R. (2021) *The Montreal Protocol protects the terrestrial carbon sink*, Nature 596(7872): 384–388, 384 (“Overall, at the end of the century, worldAvd warms by an additional 2.5 K (2.4–2.7 K) above the RCP 6.0

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baseline in worldProj. Of this warming, 1.7 K comes from the previously explored19 additional radiative forcing due to the higher CFC concentrations in worldProj. Newly quantified here is the additional warming of global-mean air temperature of 0.85 K (0.65–1.0 K)—half as much again—that arises from the higher atmospheric CO_2 concentrations due to the damaging effect of UV radiation on terrestrial carbon stores.”).

[211] Xu Y., Zaelke D., Velders G. J. M., & Ramanathan V. (2013) *The role of HFCs in mitigating 21st century climate change*, Atmos. Chem. & Phys. 13(12): 6083–6089, 6083 (“Here we show that avoiding production and use of high-GWP (global warming potential) HFCs by using technologically feasible low-GWP substitutes to meet the increasing global demand can avoid as much as another 0.5 ºC warming by the end of the century. This combine mitigation on SLCPs would cut the cumulative warming since 2005 by 50% at 2050 and by 60% at 2100 from the CO_2-only mitigation scenarios, significantly reducing the rate of warming and lowering the probability of exceeding the 2 ºC warming threshold during this century.”). *For an updated assessment of HFC mitigation from policy adopted in the lead-up to the Kigali Amendment (KA) and locked-in with the entry into force of the KA,* see Velders G. J. M., Daniel J. S., Montzka S. A., Vimont I., Rigby M., Krummel P. B., Muhle J., O’Doherty S., Prinn R. G., Weiss R. F., & Young D. (2022) *Projections of hydrofluorocarbon (HFC) emissions and the resulting global warming based on recent trends in observed abundances and current policies*, Atmos. Chem. Phys. 22(9): 6087–6101, 6099 (“Projected mixing ratios, radiative forcing, and globally averaged temperature changes are calculated from the projected HFC emissions. The 2050 radiative forcing is 0.13–0.18 Wm^{-2} in the current policies K-I scenario and drops to 0.08–0.09 Wm^{-2} when the additional Kigali Amendment controls are considered (in KA-2022). In the current policies K-I scenario, the HFCs are projected to contribute 0.14–0.31 °C to the global surface warming in 2100, compared to 0.28–0.44 °C without policies. Following the Kigali Amendment, the surface warming of HFCs is reduced to about 0.05 °C in 2050 and 0.04 °C in 2100 (KA-2022. In a hypothetical scenario with a full phaseout of HFCs production and consumption in 2023, the contribution is reduced to about 0.01 °C in 2100.”).

[212] Montzka, S.A. and Velders, G.J.M. (Lead Authors), Krummel, P.B., Mühle, J., Orkin, V.L., Park, S., Shah, N., and Walter-Terrinoni, H. (2018). *Hydrofluorocarbons (HFCs),* Chapter 2 in *Scientific Assessment of Ozone Depletion: 2018*, *Global Ozone Research and Monitoring Project–Report No. 58*. World Meteorological Organization, Geneva, Switzerland. 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.”).

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

[214] World Meteorological Organization, United Nations Environment Programme, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, & 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 ºC to less than 0.1 ºC (Figure ES-4). If the global production of HFCs were to cease in 2020, the surface temperature contribution of the HFC emissions would stay below 0.02 ºC for the whole 21st century. The magnitude of the avoided temperature increase, due to the provisions of the Kigali Amendment (0.2 to 0.4 ºC) is substantial in the context of the 2015 UNFCCC Paris Agreement, which aims to limit global temperature rise to well below 2.0 ºC above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 ºC.”); 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

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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.").

[215] World Meteorological Organization, United Nations Environment Programme, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, & 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.").

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

[217] United Nations Treaty Collection, *Amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer* (*last visited* 11 May 2022).

[218] American Innovation and Manufacturing Act, Pub. L. No. 116-260, §103(h)(1) (codified at 42 U.S.C. § 7675 (h)(1)). *See also* U.S. Environmental Protection Agency, Proposed Rule - Phasedown of Hydrofluorocarbons: Establishing the Allowance Allocation and Trading Program under the AIM Act (*last visited* 12 November 2021).

[219] *See* https://www.hfcbans.com/usa.html (*last visited* 12 November 2021). States with finalized HFC prohibitions include: California, Colorado, Delaware, Maine, Maryland, Massachusetts, New Jersey, New York, Rhode Island, Washington, Vermont, and Virginia. States with proposed bans include: Connecticut, Hawaii, New Mexico, Oregon, Pennsylvania, and Texas.

[220] White House Briefing Room, *A Message to the Senate on the Amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer* (16 November 2021) ("TO THE SENATE OF THE UNITED STATES: With a view to receiving the advice and consent of the Senate to ratification, I transmit herewith the Amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer (the "Montreal Protocol"), adopted at Kigali on October 15, 2016, by the Twenty-Eighth Meeting of the Parties to the Montreal Protocol (the "Kigali Amendment"). The report of the Department of State is also enclosed for the information of the Senate. The principal features of the Kigali Amendment provide for a gradual phasedown in the production and consumption of hydrofluorocarbons (HFCs), which are alternatives to ozone-depleting substances being phased out under the Montreal Protocol, as well as related provisions concerning reporting, licensing, control of trade with non-Parties, and control of certain byproduct emissions."); *discussed in* Mason J. (16 November 2021) *White House sends Kigali amendment on climate-warming gases to Senate*, REUTERS.

[221] Portmann R. W., Daniel J. S., & Ravishankara A. R. (2012) *Stratospheric Ozone Depletion Due to Nitrous Oxide: Influences of Other Gases*, PHILOS. TRANS. R SOC. LOND. B BIOL. SCI. 367(1593): 1256–1264, 1262 ("By 2008, anthropogenic N_2O was the most significant ozone-destroying compound being emitted. Owing to the phase-out of

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anthropogenic halocarbon emissions, it is likely to become even more dominant in the near future."). *See also* Porter I. (2019) *Mitigation of Nitrous Oxide Emissions*, Presentation at 31st Meeting of the Parties to the Montreal Protocol ("By 2050, lack of controls on N_2O will undo 25% of the benefit gained by the Montreal Protocol to reducing ODS from the ozone layer.").

[222] World Meteorological Organization, United Nations Environment Programme, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, & 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_2O to radiative forcing has continued to rise, reaching 0.19 W m^{-2} in 2016, approximately 10% that of CO_2.").

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

[224] Environmental Protection Agency (2012) GLOBAL ANTHROPOGENIC NON-CO_2 GREENHOUSE GAS EMISSIONS: 1990–2030, 41 ("Between 1990 and 2005, N2O emissions from production of nitric and adipic acid has decreased 37 percent, from 200 $MtCO_2e$ to 126 $MtCO_2e$ (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 N2Oemissions from this source, whereas the OECD is estimated to account for 68 percent of global emissions in 2005.").

[225] Environmental Protection Agency (2019) GLOBAL NON-CO_2 GREENHOUSE GAS EMISSION PROJECTIONS & MITIGATION: 2015–2050, 29 ("Taken together, the top 5 countries in terms of baseline emissions represent 85% of all potential global abatement in the source category in 2030. China alone represents 67% of total abatement potential, in part because of its high production capacity and lower adoption of emission controls relative to other large producers of nitric and adipic acid.").

[226] Balafoutis A., Beck B., Fountas S., Vangeyte J., van der Wal T., Soto I., Gómez-Barbero M., Barnes A., & Eory V. (2017) *Precision Agriculture Technologies Positively Contributing to GHG Emissions Mitigation, Farm Productivity and Economics*, SUSTAINABILITY 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%.").

[227] SOP, Save Our Planet (*last visited* 11 May 2022).

[228] 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."). *See also* Maris S. C., Capra F., Ardenti F., Chiodini M. E., Boselli R., Taskin E., Puglisi E., Bertora C., Poggianella L., Amaducci S., Tabaglio V., & Fiorini A. (2021) *Reducing N Fertilization without Yield Penalties in Maize with a Commercially Available Seed Dressing*, AGRONOMY 11(3): 407 ("[W]e concluded that under our experimental conditions SCM [SOP® COCUS MAIZE+] may be used for reducing N [nitrogen] input (-30%) and N_2O emissions (-23%), while contemporarily maintaining maize yield. Hence, SCM can be considered an available tool to improve agriculture's alignment to the United Nation Sustainable Development Goals (UN SDGs) and to comply with Europe's Farm to Fork strategy for reducing N-fertilizer inputs.").

[229] Butler A. H., Daniel J. S., Portmann R. W., Ravishankara A. R., Young P. J., Fahey D. W., & Rosenlof K. H. (2016) *Diverse policy implications for future ozone and surface UV in a changing climate*, ENV. RES. LETT. 11(6): 064017 ("A key point is that if the world were to achieve reductions of CO_2 and CH_4 concentrations to RCP 2.6 levels, N_2O mitigation would become important to avoid exacerbation of both climate change and ozone layer depletion.").

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

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[231] United Nations Environment Programme & World Meteorological Organization (2011) INTEGRATED ASSESSMENT OF BLACK CARBON AND TROPOSPHERIC OZONE, 239, 246 ("Evaluating global mean temperature change, it was found that the targeted measures to reduce emissions of methane and BC could greatly reduce warming rates over the next few decades (Figure 6.1; Box 6.1). When all measures are fully implemented, warming during the 2030s relative to the present would be only half as much as in the reference scenario. In contrast, even a fairly aggressive strategy to reduce CO_2 emissions, as for the CO_2-measures scenario, does little to mitigate warming until after the next 20-30 years (Box 6.2)."; "Large impacts of the measures examined here were also seen for the Arctic despite the minimal amount of emissions currently taking place there. This occurs due to the high sensitivity of the Arctic both to pollutants that are transported there from remote sources and to radiative forcing that takes place in areas of the northern hemisphere outside the Arctic. The 16 measures examined here, including the measures on pellet stoves and coal briquettes, reduce warming in the Arctic by 0.7 ºC (range 0.2 to 1.3 ºC) at 2040. This is a large portion of the 1.1 ºC (range 0.7 to 1.7 ºC) warming projected under the reference scenario for the Arctic, and hence implementation of the measures would be virtually certain to substantially slow, but not halt, the pace of Arctic climate change.").

[232] Ocko I. B., Sun T., Shindell D., Oppenheimer M., Hristov A. N., Pacala S. W., Mauzerall D. L., Xu Y., & Hamburg S. P. (2021) *Acting rapidly to deploy readily available methane mitigation measures by sector can immediately slow global warming*, ENVIRON. RES. LETT. 16(5): 054042 ("Pursuing all mitigation measures now could slow the global-mean rate of near-term decadal warming by around 30%, avoid a quarter of a degree centigrade of additional global-mean warming by midcentury, and set ourselves on a path to avoid more than half a degree centigrade by end of century. On the other hand, slow implementation of these measures may result in an additional tenth of a degree of global-mean warming by midcentury and 5% faster warming rate (relative to fast action), and waiting to pursue these measures until midcentury may result in an additional two tenths of a degree centigrade by midcentury and 15% faster warming rate (relative to fast action).").

[233] Sun T., Ocko I. B., Hamburg S. P., (2022) *The value of early methane mitigation in preserving Arctic summer sea ice*, ENVIRON. RES. LETT. 17: 044001 ("While drastic cuts in carbon dioxide emissions will ultimately control the fate of Arctic summer sea ice, we show that simultaneous early deployment of feasible methane mitigation measures is essential to avoiding the loss of Arctic summer sea ice this century. In fact, the benefit of combined methane and carbon dioxide mitigation on reducing the likelihood of a seasonally ice-free Arctic can be greater than the simple sum of benefits from two independent greenhouse gas policies. The extent to which methane mitigation can help preserve Arctic summer sea ice depends on the implementation timeline. The benefit of methane mitigation is maximized when all technically feasible measures are implemented within this decade, and it decreases with each decade of delay in implementation due to its influence on end-of-century temperature. A key insight is that methane mitigation substantially lowers the risk of losing Arctic summer sea ice across varying levels of concomitant carbon dioxide mitigation.").

[234] Bonan D. B., Schneider T., Eisenman I., & Wills R. C. J. (2021) *Constraining the Date of a Seasonally Ice-Free Arctic Using a Simple Model*, GEOPHYS. RES. LETT. 48(18): 1–12, 1 ("Under a high-emissions scenario, an ice-free Arctic will likely (>66% probability) occur between 2036 and 2056 in September and between 2050 and 2068 from July to October. Under a medium-emissions scenario, the "likely" date occurs between 2040 and 2062 in September and much later in the 21st century from July to October.").

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

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

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[237] Centre for Climate Repair at Cambridge, *Marine Cloud Brightening MCB*, Research Themes, Restoring Broken Climate Systems (*last visited* 16 July 2021) ("Several routes for refreezing are being developed. One involves the manipulation of sea ice to increase the overall rate of growth during the early winter. Two different approaches have been cited which have not received in-depth research: *the breaking up of newly formed sea ice* in the winter in order to increase the thickness of some areas whilst consequently exposing more sea water to cold air which could increase the overall rate of formation of ice whilst also providing zones of thicker ice which could potentially remain frozen over a complete summer; *the spraying of sea-water* onto the top of ice, thereby causing more ice to form."). *See generally* Carnegie Climate Governance Initiative (2021) *Climate-Altering Approaches and the Arctic*, Policy Brief, 2nd ed. (discussing enhancing surface albedo and marine cloud brightening to slow Arctic warming); *and* Field L., Ivanova D., Bhattacharyya S., Mlaker V., Sholtz A., Decca R., Manzara A., Johnson D., Christodoulou E., Walter P., & Katuri K. (2018) *Increasing Arctic Sea Ice Albedo Using Localized Reversible Geoengineering*, Earth's Future 6(6):882–901 (discussing testing hollow silica beads to enhance albedo of Arctic sea ice).

[238] Jackson R. B., *et al.* (2021) *Atmospheric methane removal: a research agenda*, Philos. Trans. R. Soc. A 379: 1–17, 1 ("Atmospheric methane removal may be needed to offset continued methane release and limit the global warming contribution of this potent greenhouse gas. Eliminating most anthropogenic methane emissions is unlikely this century, and sudden methane release from the Arctic or elsewhere cannot be excluded, so technologies for negative emissions of methane may be needed. Carbon dioxide removal (CDR) has a well-established research agenda, technological foundation and comparative modelling framework [23–28]. No such framework exists for methane removal. We outline considerations for such an agenda here. We start by presenting the technological Mt CH_4 yr^{-1} considerations for methane removal: energy requirements (§2a), specific proposed technologies (§2b), and air processing and scaling requirements (§2c). We then outline the climate and air quality impacts and feedbacks of methane removal (§3a) and argue for the creation of a Methane Removal Model Intercomparison Project (§3b), a multi-model framework that would better quantify the expected impacts of methane removal. In §4, we discuss some broader implications of methane removal."). *See also* Abernethy S., O'Connor F. M., Jones C. D., & Jackson R. B. (2021) *Methane removal and the proportional reductions in surface temperature and ozone*, Philos. Trans. R. Soc. A 379: 1–13, 6 ("Due to the temporal nature of effective cumulative removal, comparisons between methane and carbon dioxide depend on the timescale of interest. The equivalent of MCR for carbon dioxide, the TCRE, is 0.00048 ± 0.0001°C per Pg CO_2 [38], two orders of magnitude smaller than our MCR estimate of 0.21 ± 0.04°C per effective Pg CH_4 removed (figure 2). Accounting for the time delay for carbon dioxide removal due to the lagged response of the deep ocean, the TCRE for CO_2 removal may be even lower [39]. If 1 year of anthropogenic emissions was removed (0.36 Pg CH_4 [3] and 41.4 Pg CO_2 [40]), the transient temperature impact would be almost four times larger for methane than for CO_2 (0.075°C compared to 0.02°C). Using this example, however, maintaining a steady-state response of 0.36 Pg CH_4 effectively removed would require the ongoing removal of roughly 0.03Pg CH_4 yr^{-1}, since a removal rate of E/τ is required to maintain an effective cumulative removal of E."). *For more history on this proposal, see* Jackson R. B., Solomon E. I., Canadell J. G., Cargnello M., & Field C. B. (2019) *Methane removal and atmospheric restoration*, Nat. Sustain. 2: 436–438, 436 ("In contrast to negative emissions scenarios for CO_2 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_4 currently in the atmosphere. Rather than capturing and storing the methane, the 3.2 Gt of CH_4 could be oxidized to CO_2, a thermodynamically favourable reaction…. In total, the reaction would yield 8.2 additional Gt of atmospheric CO_2, equivalent to a few months of current industrial CO_2 emissions, but it would eliminate approximately one sixth of total radiative forcing. As a result, methane removal or conversion would strongly complement current CO_2 and CH_4 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_2 and N_2O."). Klaus Lackner critiqued the Jackson *et al.* article in a published response, arguing that implementing zeolite mechanisms to facilitate CH_4 removal is not practical. Lackner noted CH_4 removal faces the challenge of extreme dilution in the atmosphere, so "the amount of air that would need to be moved [to facilitate CH_4 removal] would simply be too great" to be economically feasible. However, Lackner did note passive methods of CH_4 removal through the use of zeolites may still be a viable solution. Lackner further argues that N_2O 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_2 as suggested in the original study. *See* Jackson R. B., Solomon

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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_2 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_2 greenhouse gases by large-scale atmospheric solar photocatalysis*, PROG. ENERGY COMBUST. SCI. 60: 68–96.

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

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

[241] Advanced Research Projects Agency-Energy (2 December 2021) *U.S. Department of Energy Awards $35 Million for Technologies to Reduce Methane Emissions*, Press Release ("The following teams selected for the REMEDY program will work to directly address the more than 50,000 engines, 300,000 flares, and 250 mine shafts that are producing methane emissions. **Natural Gas Engines** **MAHLE Powertrain** (Plymouth, MI) will develop a catalytic system to oxidize methane in the exhaust gas of lean-burn natural gas fired engines. (Selection amount: $3,257,089) **Colorado State University** (Fort Collins, CO) will develop hardware to redirect methane emissions to the engine's turbocharger, reducing emissions and improving fuel efficiency. (Selection amount: $1,500,000) **Marquette University** (Milwaukee, WI) will demonstrate their Mixed Controlled Combustion (MCC) system which can be retrofitted into lean-burn engines. (Selection amount: $3,975,058) **INNIO's Waukesha Gas Engines** (Waukesha, WI) will develop a new line of pistons fabricated with friction welding. The new pistons reduce the space for methane to "slip" past the combustion zone in the engine and can be installed as part of normal engine maintenance programs. (Selection amount: $2,230,693) **Texas A&M University** (College Station, TX) will use plasma and advanced engine controls to reduce methane slip. The technology is targeting the large two-stroke engines used by gas pipeline companies. (Selection amount: $2,824,814). **Flares** **Advanced Cooling Technologies, Inc**. (Lancaster, PA) will adapt their combustor design to ensure 99.5% methane destruction efficiency for the highly variable gas sent to flares. The combustors will be made of silicon carbide, which can withstand more than 2500 degrees Fahrenheit, using a new 3D printing process. (Selection amount: $3,300,000) **Cimarron Energy, Inc**. (Houston, TX) proposes a hybrid flare design coupled with advanced controls to ensure 99.5% destruction efficiency for flares that handle both high- and low-pressure gas streams. (Selection amount: $1,000,000) **University of Michigan** (Ann Arbor, MI) will use additive manufacturing and machine learning to scale up their advanced burner. The burner will be incorporated into a new flare system design that is robust to cross winds and low load conditions which can lead to poor methane destruction efficiency. (Selection amount: $2,881,762) **University of Minnesota** (Minneapolis, MN) will use plasma-assisted combustion to enhance flare methane destruction efficiency. (Selection amount: $2,141,876). **Methane from Coal Mine Shafts** **Johnson Matthey, Inc.** (Wayne, PA) is developing new technology, which uses a noble metal catalyst to combust the dilute methane in coal mine ventilation systems. (Selection amount: $4,346,015) **Massachusetts Institute of Technology** (Cambridge, MA) is developing a low-cost copper-based catalyst for reducing methane

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emissions. (Selection amount: $2,020,903) **Precision Combustion, Inc.** (North Haven, CT) proposes an innovative modular system that promotes methane reaction and manages thermal loads in a novel reactor design. (Selection amount: $3,720,317)").

[242] Bloomer L., Sun X., Dreyfus G., Ferris T., Zaelke D., & Schiff C. (2022) *A Call to Stop Burning Trees in the Name of Climate Mitigation*, VT. J. ENVTL. LAW 23: 94–123, 94 ("Burning trees for energy delivers a one-two punch against climate change mitigation efforts. Harvesting woody biomass reduces the sequestration potential of forest carbon sinks, while the combustion of woody biomass releases large quantities of carbon into the air.1 Forest regrowth may not offset these emissions for many decades2—well beyond the time the world has left to slow warming to avoid catastrophic impacts from climate change."). *See also* Moomaw W. R., Masino S. A., & Faison E. K. (2019) *Intact Forests in the Unites States: Proforestation Mitigates Climate Change and Serves the Greatest Good*, Perspective, FRONT. FOR. GLOB. CHANGE 2(27): 1–10, 1 ("Climate change and loss of biodiversity are widely recognized as the foremost environmental challenges of our time. Forests annually sequester large quantities of atmospheric carbon dioxide (CO_2), and store carbon above and below ground for long periods of time. Intact forests—largely free from human intervention except primarily for trails and hazard removals—are the most carbon-dense and biodiverse terrestrial ecosystems, with additional benefits to society and the economy. … The recent *1.5 Degree Warming Report* by the Intergovernmental Panel on Climate Change identifies *reforestation* and *afforestation* as important strategies to increase negative emissions, but they face significant challenges: afforestation requires an enormous amount of additional land, and neither strategy can remove sufficient carbon by growing young trees during the critical next decade(s). In contrast, growing existing forests intact to their ecological potential—termed *proforestation*—is a more effective, immediate, and low-cost approach that could be mobilized across suitable forests of all types. Proforestation serves the greatest public good by maximizing co-benefits such as nature-based biological carbon sequestration and unparalleled ecosystem services such as biodiversity enhancement, water and air quality, flood and erosion control, public health benefits, low impact recreation, and scenic beauty."); World Wildlife Fund (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."); Griscom B. W., *et al.* (2017) *Natural climate solutions*, PROC. NAT'L. ACAD. SCI. 114(44): 11645–11650, 11645 ("Better stewardship of land is needed to achieve the Paris Climate Agreement goal of holding warming to below 2 °C; however, confusion persists about the specific set of land stewardship options available and their mitigation potential. To address this, we identify and quantify "natural climate solutions" (NCS): 20 conservation, restoration, and improved land management actions that increase carbon storage and/or avoid greenhouse gas emissions across global forests, wetlands, grasslands, and agricultural lands. We find that the maximum potential of NCS—when constrained by food security, fiber security, and biodiversity conservation—is 23.8 petagrams of CO_2 equivalent ($PgCO_2e$) y^{-1} (95% CI 20.3–37.4). This is ≥30% higher than prior estimates, which did not include the full range of options and safeguards considered here. About half of this maximum (11.3 $PgCO_2e\ y^{-1}$) represents cost-effective climate mitigation, assuming the social cost of CO_2 pollution is ≥100 USD $MgCO_2e^{-1}$ by 2030. Natural climate solutions can provide 37% of cost-effective CO_2 mitigation needed through 2030 for a >66% chance of holding warming to below 2 °C. One-third of this cost-effective NCS mitigation can be delivered at or below 10 USD $MgCO_2{}^{-1}$. Most NCS actions—if effectively implemented—also offer water filtration, flood buffering, soil health, biodiversity habitat, and enhanced climate resilience. Work remains to better constrain uncertainty of NCS mitigation estimates. Nevertheless, existing knowledge reported here provides a robust basis for immediate global action to improve ecosystem stewardship as a major solution to climate change."); *and* Raven P., *et al.* (11 February 2021) *Letter Regarding Use of Forests for Bioenergy*, WOODWELL CLIMATE RESEARCH CENTER ("Trees are more valuable alive than dead both for climate and for biodiversity. To meet future net zero emission goals, your governments should work to preserve and restore forests and not to burn them.").

[243] Goldstein A., Noon M. L., Ledezma J. C., Roehrdanz P. R., Raghav S., McGreevey M., Stone C., Shrestha S., Golden Kroner R., Hole D., & Turner W. (2021*) Irrecoverable Carbon: the places we must protect to avert climate catastrophe, Conservation International*, 7 (" 'Irrecoverable carbon' refers to the vast stores of carbon in nature that are vulnerable to release from human activity and, if lost, could not be restored by 2050 — when the world must reach net-zero emissions to avoid the worst impacts of climate change... There are high concentrations of irrecoverable

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carbon in the Amazon (31.5 Gt), the Congo Basin (8.1 Gt), and New Guinea (7.3 Gt). Other important irrecoverable carbon reserves are located in the Pacific Northwest of North America, the Valdivian forests of Chile, the mangroves and swamp forests of Guyana, the peatlands of Northern Scotland, Niger Delta's mangroves, Cambodia's Tonle Sap Lake, the Scandinavian and Siberian boreal forests, and the eucalyptus forest of Southeast Australia, among others."). *See also* Goldstein A., *et al.* (2020) *Protecting irrecoverable carbon in Earth's ecosystems*, NAT. CLIM. CHANGE 10(4): 287–295; *and* Noon M. L., Goldstein A., Ledezma J. C., Roehrdanz P. R., Cook-Patton S. C., Spawn-Lee S. A., Wright T. M., Gonzalez-Roglich M., Hole D. G., Rockström J., & Turner W. R. (2021) *Mapping the irrecoverable carbon in Earth's ecosystems*, NAT. SUSTAIN. 1–10.

[244] Lenton T. M., Rockstrom J., Gaffney O., Rahmstorf S., Richardson K., Steffen W., & Schellnhuber H. J. (2019) *Climate tipping points—too risky to bet against*, Comment, NATURE, 575: 592–595, 593 ("Estimates of where an Amazon tipping point could lie range from 40% deforestation to just 30% forest-cover loss. About 17% has been lost since 1970. The rate of deforestation varies with changes in policy. Finding the tipping point requires models that include deforestation and climate change as interacting drivers, and that incorporate fire and climate feedbacks as interacting tipping mechanisms across scales."). *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 20–25% deforestation."); *and* Hoegh-Guldberg O., Jacob D., & Taylor M. (2018) *Chapter 3: Impacts of 1.5 ºC of Global Warming on Natural and Human Systems*, *in* GLOBAL WARMING OF 1.5 °C, *Special Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 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.").

[245] Douville H., *et al.* (2021) *Chapter 8: Water Cycle Changes*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 8-112 ("Both deforestation and drying are projected to increase by 2100, resulting in a worst-case scenario of up to a 50% loss in forest cover by 2050 (Soares-Filho et al., 2006; Boisier et al., 2015; Steege et 50 al., 2015; Gomes et al., 2019).").

[246] Wang-Erlandsson L., *et al.* (2022) *A planetary boundary for green water*, NAT. REV. EARTH ENVIRON.; *as discussed in* Stockhom Resilience Center (26 April 2022) *Freshwater boundary exceeds safe limits* ("Now researchers have explored the water boundary in more detail. The authors argue that previous assessments did not sufficiently capture the role of green water and particularly soil moisture for ensuring the resilience of the biosphere, for securing land carbon sinks, and for regulating atmospheric circulation. "The Amazon rainforest depends on soil moisture for its survival. But there is evidence that parts of the Amazon are drying out. The forest is losing soil moisture as a result of climate change and deforestation," says Arne Tobian, second author and PhD candidate at the Stockholm Resilience Centre and Potsdam Institute for Climate Impact Research. "These changes are potentially pushing the Amazon closer to a tipping point where large parts could switch from rainforest to savannah-like states," he adds.").

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

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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.").

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

[249] Canadell J. G., *et al.* (2021) *Chapter 5: Global Carbon and other Biogeochemical Cycles and Feedbacks*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), Table 5.6 and 5-740 ("To estimate an upper limit on the impact of Amazon forest dieback on atmospheric CO_2, we consider the *very unlikely* limiting case of negligible direct-CO_2 effects (Section 5.4.1). Emergent constraint approaches (Section 5.4.6) may be used to estimate an overall loss of tropical land carbon due to climate change alone, of around 50 PgC per °C of tropical warming (Cox et al., 2013; Wenzel et al., 2014). This implies an upper limit to the release of tropical land carbon of <200 PgC over the 21st century (assuming tropical warming of <4°C and no CO_2-fertilization), which translates to $dCO_2/dt<0.5$ ppm yr^{-1}. Boreal forest dieback is not expected to change the atmospheric CO_2 concentration substantially because forest loss at the south is partly compensated by: (i) temperate forest invasion into previously boreal areas; and (ii) boreal forest gain at the north (Friend et al., 2014; Kicklighter et al., 2014; Schaphoff et al., 2016) (medium confidence). An upper estimate of this magnitude, based on statistical modelling of climate change alone, is of 27 Pg vegetation carbon loss in the southern boreal forest, which is roughly balanced by gains in the northern zone (Koven, 2013).").

[250] Duffy K. A., Schwalm C. R., Arcus V. L., Koch G. W., Liang L. L., & Schipper L. A. (2021) *How close are we to the temperature tipping point of the terrestrial biosphere?*, Sci. Adv. 7(3): eaay1052, 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 biodiversity11, their ability to sequester additional carbon in trees is waning. In the 1990s intact tropical forests removed 17% of anthropogenic CO_2 emissions. This declined to an estimated 6% in the 2010s, because the pan-tropical weighted average per unit area sink strength declined by 33%, forest area decreased by 19% and anthropogenic CO_2 emissions increased by 46%. Although tropical forests are more immediately threatened by deforestation46 and degradation47, and the future carbon balance will also depend on secondary forest dynamics48 and forest restoration plans49, our analyses show that they are also affected by atmospheric chemistry and climatic changes. Given that the intact tropical forest carbon sink is set to end sooner than even the most pessimistic climate driven vegetation models predict4,5, our analyses suggest that climate change impacts in the tropics may become more severe than predicted. Furthermore, the carbon balance of intact tropical forests will only stabilize once CO_2 concentrations and the climate stabilizes."). *See also* Intergovernmental Panel on Climate Change (2021) *Summary for Policymakers*, *in* Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), SPM-26 ("Based on model projections, under the intermediate scenario that stabilizes atmospheric CO_2 concentrations this century (SSP2-4.5), the rates of CO_2 taken

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up by the land and oceans are projected to decrease in the second half of the 21st century (*high confidence*). Under the very low and low GHG emissions scenarios (SSP1-1.9, SSP1-2.6), where CO_2 concentrations peak and decline during the 21st century, land and oceans begin to take up less carbon in response to declining atmospheric CO_2 concentrations (*high confidence*) and turn into a weak net source by 2100 under SSP1-1.9 (*medium confidence*). It is very unlikely that the combined global land and ocean sink will turn into a source by 2100 under scenarios without net negative emissions32 (SSP2-4.5, SSP3-7.0, SSP5-8.5)… Additional ecosystem responses to warming not yet fully included in climate models, such as CO_2 and CH_4 fluxes from wetlands, permafrost thaw and wildfires, would further increase concentrations of these gases in the atmosphere (*high confidence*).").

[251] 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).").

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

[253] 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.").

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

[255] Intergovernmental Panel on Climate Change (2019) *Summary for Policymakers*, *in* THE OCEAN AND CRYOSPHERE IN A CHANGING CLIMATE, *Special Report of the Intergovernmental Panel on Climate Change*, Pörtner H.-O., *et al.*

(eds.), 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.").

[256] Booth M. S. (2018) *Not Carbon Neutral: Assessing the Net Emissions Impact of Residues Burned for Bioenergy*, Environ. Res. Lett. 13: 1–10, 8 ("For bioenergy to offer genuine climate mitigation, it is essential to move beyond the assumption of instantaneous carbon neutrality. The [net emissions impact (NEI)] approach provides a simple means to estimate net bioenergy emissions over time, albeit one that tends to underestimate actual impacts. The model finds that for plants burning locally sourced wood residues, from 41% (extremely rapid decomposition) to 95% (very slow decomposition) of cumulative direct emissions should be counted as contributing to atmospheric carbon loading by year 10. Even by year 50 and beyond, the model shows that net emissions are a significant proportion of direct emissions for many fuels."). *See also* Sterman J. D., *et al.* (2018) *Does Replacing Coal with Wood Lower CO_2 Emissions? Dynamic Lifecycle Analysis of Wood Bioenergy*, Environ. Res. Lett. 13: 1–10, 8 ("Scenario 2 shows the realistic case with the combustion efficiency and supply chain emissions estimated for wood pellets (supplementary table S5), again assuming 25% of the biomass is harvested by thinning. Because production and combustion of wood generate more CO2 than coal, the first impact of bioenergy use is an increase in atmospheric CO2. Regrowth gradually transfers C from the atmosphere to biomass and soil C stocks, leading to a carbon debt payback time of 52 years; after 100 years CO2 remains 62% above the zero C case."); *and* Bloomer L., Sun X., Dreyfus G., Ferris T., Zaelke D., & Schiff C. (2022) *A Call to Stop Burning Trees in the Name of Climate Mitigation*, Vt. J. Envtl. Law 23: 94–123.

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

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

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

- Incentivize forest and ecosystem conservation and forest landscape restoration;
- Catalyze private sector investment, finance, and action to conserve critical carbon sinks;
- Build long-term capacity and support the data and monitoring systems that enhance accountability;
- Increase ambition for climate and conservation action.").

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[260] Dreyfus G. B., Xu Y., Shindell D., Zaelke D., & Ramanathan V. (2022*) Mitigating Climate Disruption in Time: a self-consistent approach for avoiding both near-term and long-term global warming*, PROC. NAT'L. ACAD. SCI. ("We find that mitigation measures that target only decarbonization are essential for strong long-term cooling but can result in weak near-term warming (due to unmasking the cooling effect of co-emitted aerosols) and lead to temperatures exceeding 2°C before 2050. In contrast, pairing decarbonization with additional mitigation measures targeting short-lived climate pollutants (SLCPs) and N_2O, slows the rate of warming a decade or two earlier than decarbonization alone and avoids the 2°C threshold altogether. These non-CO_2 targeted measures when combined with decarbonization can provide net cooling by 2030, reduce the rate of warming from 2030 to 2050 by about 50%, roughly half of which comes from methane, significantly larger than decarbonization alone over this timeframe.").

[261] United Nations (9 August 2021) *Guterres: The IPCC Report is a code red for humanity*, UN Regional Information Centre for Western Europe.

[262] Intergovernmental Panel on Climate Change (2018) *Summary for Policymakers*, *in* GLOBAL WARMING OF 1.5 °C, *Special Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), SPM-6 ("Human activities are estimated to have caused approximately 1.0 ºC of global warming above pre-industrial levels, with a *likely* range of 0.8 ºC to 1.2 ºC. Global warming is *likely* to reach 1.5 ºC between 2030 and 2052 if it continues to increase at the current rate. (*high confidence*)."). In addition to cutting CO_2 emissions and emissions of the super climate pollutants, the IPCC 1.5 ºC Report also calculates the need for significant CO_2 removal. *Id.*, at 17 ("C.3. All pathways that limit global warming to 1.5°C with limited or no overshoot project the use of carbon dioxide removal (CDR) on the order of 100–1000 $GtCO_2$ over the 21st century.").

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

[264] 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

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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.").

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

A CALL TO STOP BURNING TREES IN THE NAME OF CLIMATE MITIGATION

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INTRODUCTION

Burning trees for energy delivers a one-two punch against climate change mitigation efforts. Harvesting woody biomass reduces the sequestration potential of forest carbon sinks, while the combustion of woody biomass releases large quantities of carbon into the air.[1] Forest regrowth may not offset these emissions for many decades[2]—well beyond the time the world has left to slow warming to avoid catastrophic impacts from climate change.

Further, harvesting forests for fuel harms ecosystems and contributes to environmental injustice. Destroying existing forests impairs biodiversity and ecosystems. Similarly, replacing natural forests with bioenergy plantations

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[1] *Forest Bioenergy, Carbon Capture & storage, & Carbon Dioxide Removal: An Update*, EUR. ACADS. SCI. ADVISORY COUNCIL 2 (2019), https://easac.eu/fileadmin/PDF_s/reports_statements/Negative_Carbon/EASAC_Commentary_Forest_Bioenergy_Feb_2019_FINAL.pdf; Timothy D. Searchinger et al., *Europe's Renewable Energy Directive Poised to Harm Global Forests*, 9 NATURE COMMC'N 1, 2 (2018).

[2] *See* Thomas Buchholz, John S. Gunn, & Benktesh Sharma, *When Biomass Electricity Demand Prompts Thinnings in Southern US Pine Plantations: A Forest Sector Greenhouse Gas Emissions Case Study*, FRONTIERS FORESTS & GLOB. CHANGE, May 10, 2021, at 1, 8 (finding that it takes more than 40 years for emissions from burning biomass derived from forest thinning to reach parity with emissions from fossil fuel-powered energy generation); Thomas Walker et al., *Carbon Accounting for Woody Biomass from Massachusetts (USA) Managed Forests: A Framework for Determining the Temporal Impacts of Wood Biomass Energy on Atmospheric Greenhouse Gas Levels*, 32 J. SUSTAINABLE ENERGY 130, 147–148 (2013) (discussing the greenhouse gas impact of switching from fossil fuels to woody biomass for energy generation); Holtsmark Bjart, *Harvesting in Boreal Forests and the Biofuel Carbon Debt*, 112 CLIMATIC CHANGE 415–428 (2011) (discussing the carbon debt incurred by harvesting boreal forests for energy).

degrades ecosystems.[3] Increased reliance on bioenergy also threatens food and water security and could intensify social conflicts.[4] In the United States, the wood pellet industry exacerbates environmental injustice.[5]

With little time left to achieve a sustainable and inclusive future, burning forests for energy contributes to warming in the near-term and is not a viable climate solution. Communities across the world are already suffering from the consequences of 1.2ºC of warming.[6] The Intergovernmental Panel on Climate Change (IPCC) and other experts warn that countries must make deep cuts to emissions within the next 10 years and continue reducing emissions through mid-century, including through carbon removal.[7] Countries must make these deep cuts to meet the Paris Agreement's target of limiting warming to well below 2ºC above pre-industrial levels.[8] At the same

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[3] Thomas Walker et al., *Carbon Accounting for Woody Biomass from Massachusetts (USA) Managed Forests: A Framework for Determining the Temporal Impacts of Wood Biomass Energy on Atmospheric Greenhouse Gas Levels*, 32 J. Sustainable Energy 130, 145 (2013) (discussing the greenhouse gas impact of switching from fossil fuels to woody biomass for energy generation).

[4] Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Global Assessment Report XXII (2019) [hereinafter IPBES].

[5] *See* Stefan Koester & Sam Davis, *Siting of Wood Pellet Production in Environmental Justice Communities in the Southeastern United States*, 11 Env't Just. 64, 64 (Apr. 2018), https://www.liebertpub.com/doi/10.1089/env.2017.0025; Patrick Anderson & Keri Powell, Env't Integrity Project, Dirty Deception: How the Biomass Industry Skirts the Clean Air Act 5 (April 26, 2018) [hereinafter Env't Integrity Project]; Michael Grunwald, *The 'Green Energy' That Might Be Ruining the Planet*, Politico Mag., Mar. 26, 2021; Danielle Purifoy, *How Europe's Wood Pellet Appetite Worsens Environmental Racism in the South*, Southerly (Oct. 5, 2020), https://southerlymag.org/2020/10/05/how-europes-wood-pellet-appetite-worsens-environmental-racism-in-the-south/?pico_new_user=true&pico_ui=login_link.

[6] *See State of the Glob. Climate 2020: Provisional Rep.*, World Meteorological Org., https://library.wmo.int/doc_num.php?explnum_id=10444 (noting that the global mean temperature for 2020 was 1.2 ± 0.1 °C above the 1850–1900 baseline).

[7] *See* Katherine Calvin et al., *Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Dev.*, *in* Global Warming of 1.5°C 93, 112, 115–116 (Valérie Masson-Delmotte et al. eds., 2018) (describing pathways that stay within 1.5ºC as requiring more significant near-term emissions reductions); Myles Allen et al., *Summary for Policymakers, in* Glob. Warming of 1.5°C 3, 18 (Valérie Masson-Delmotte et al. eds., 2018) ("Pathways that limit global warming to 1.5°C with no or limited overshoot show clear emission reductions by 2030 (*high confidence*). All but one show a decline in global greenhouse gas emissions to below 35 $\text{GtCO}_2\text{eq yr}^{-1}$ in 2030, and half of available pathways fall within the 25–30 $\text{GtCO}_2\text{eq yr}^{-1}$ range (interquartile range), a 40–50% reduction from 2010 levels (*high confidence.*").

[8] Parties to the United Nations Framework Convention on Climate Change agreed to the Paris Agreement in 2015. U.N. Framework Convention on Climate Change Conference of the Parties, *Report of the Conference of the Parties on its twenty-first session*, U.N. Doc. FCCC/CP/2015/10/Add.1, Annex, at 3 (Jan. 29, 2016) [hereinafter *COP 21st Session Report*]. The Paris Agreement entered into force on

time, the biodiversity crisis is unprecedented and accelerating, demanding quick action to protect species and ecosystems.[9]

Yet, governments around the world categorize forest biomass as a carbon-neutral resource and promote harvesting and burning forest biomass as a strategy to meet net-zero carbon dioxide (CO_2) targets.[10] Additionally, many climate models and country-specific plans include bioenergy with carbon capture and storage (BECCS) as a carbon removal strategy.[11] But the carbon capture and storage (CCS) technology is not ready for deployment at scale.[12] And in order to characterize forest-based BECCS as a carbon removal strategy, it is necessary to adopt the false premise that it is carbon neutral to harvest and burn forests to generate power.

Before it is too late, governments must stop cutting down forests to meet renewable energy targets. They must instead invest in strategies to deploy low-emission energy sources, decrease energy demand, and protect and enhance natural carbon sinks, while also reducing emissions of short-lived climate pollutants.

November 4, 2016. *Paris Agreement–Status of Ratification*, U.N. Framework Convention on Climate Change, https://unfccc.int/process/the-paris-agreement/status-of-ratification (last visited Jan. 15, 2022). Per Article 2, the Parties agree to "[hold] the increase in the global average temperature to well below 2°C above pre-industrial levels and [pursue] efforts to limit the temperature increase to 1.5°C above pre-industrial levels…" *COP 21st Session Report* at 4.

[9] *See* IPBES, *supra* note 4, at 2 ("Human actions threaten more species with global extinction now than ever before. An average of around 25 per cent of species in assessed animal and plant groups are threatened, suggesting that around 1 million species already face extinction, many within decades, unless action is taken to reduce the intensity of drivers of biodiversity loss. Without such action, there will be a further acceleration in the global rate of species extinction, which is already at least tens to hundreds of times higher than it has averaged over the past 10 million years.").

[10] *See, e.g.*, Council Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the Promotion of the Use of Energy from Renewable Sources, Annex VI, 2018 O.J. (L 328) 185 [hereinafter Council Directive 2018/2001] (showing that "Emissions of CO_2 from fuel in use, e_u, shall be taken to be zero for biomass fuels. Emissions of non-CO_2 greenhouse gases (CH_4 and N_2O) from the fuel in use shall be included in the e_u factor."); Consolidated Appropriations Act, H.R. 133, 116th Cong. Div. G, Title IV, § 439 (2)(A) (2020) (stating that forest bioenergy policies should reflect forest bioenergy's carbon neutrality); Zhōnghuá rénmín gònghéguó kě zàishēng néngyuán fǎ (中华人民共和国可再生能源法) [Renewable Energy Law of the People's Republic of China] (promulgated by Standing Comm. Nat'l People's Cong., Feb. 28, 2005, effective Jan. 1, 2006) art. 2, 32 (China) (defining biomass as renewable energy and encouraging its development to protect the environment).

[11] *See, e.g.,* Duncan Brack & Richard King, Chatham House, Net Zero and Beyond: What Role for Bioenergy with Carbon Capture and Storage? 5 (2020) (stating that "The literature and models reviewed by SR1.5 exhibit huge variations in mitigation potential for BECCS, ranging from 1 $GtCO_2$/year to 85 $GtCO_2$/year by 2050.").

[12] *New Research: Carbon Capture and Storage is Ready but Rapid Deployment is Needed to Reach Net Zero*, Scottish Carbon Capture & Storage (Nov. 4, 2021), https://www.sccs.org.uk/news-events/recent-news/669-new-research-carbon-capture-and-storage-is-ready-but-rapid-deployment-is-needed-to-reach-net-zero.

This article begins with an overview of the scientific background of why harvesting and burning forests for energy is not a viable solution to climate change or related challenges. This background section includes an explanation of key terminology used in the article. The next section presents the European Union (EU)'s Renewable Energy Directive as a case study on the consequences of including bioenergy in renewable energy policies. Following the case study, the article examines bioenergy policies in the United States and China—the world's two largest greenhouse gas emitters. The article concludes with policy recommendations to focus government action towards reducing reliance on energy from forest biomass. These recommendations are that governments: (1) re-evaluate their bioenergy policies and ensure lifecycle accounting of forest bioenergy's climate emissions associated with harvesting and burning forest biomass; (2) end incentives for harvesting forests for fuel and invest in forest preservation, low-emission energy, and low energy demand pathways; and (3) advance international consensus on the harms from forest bioenergy, specifically the impact on climate and biodiversity.

I. EXPLANATION OF FOREST BIOENERGY AND BIOENERGY WITH CARBON CAPTURE AND STORAGE (BECCS)

The term "bioenergy" generally encompasses any form of energy derived from biomass.[13] This article considers only forest biomass, such as trees logged for bioenergy and forestry residues from thinning or other harvesting activities. The article refers to these sources as "forest biomass" or "woody biomass" and the energy derived from these sources as "forest bioenergy." Where the data is not specific to forest biomass, the article refers to "bioenergy" or "biomass" more generally.

Efforts to phase out fossil fuels are leading to a resurgence of forest bioenergy consumption in some countries.[14] This resurgence is occurring partially through co-firing or conversion of coal-fired power plants to

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[13] Off. of Energy Efficiency & Renewable Energy, *Bioenergy* Basics, U.S. DEP'T ENERGY, http://www.energy.gov/eere/bioenergy/bioenergy-basics (last visited Jan. 15, 2022).

[14] *See* CHARLES MOORE & MALGORZATA KASPRZAK, SANDBAG, PLAYING WITH FIRE: AN ASSESSMENT OF PLANS TO BURN BIOMASS IN EU COAL POWER STATIONS 7–8 fig. 2 (2019) (showing E.U. member states use of biomass as a fossil fuel substitute through an increase in biomass consumption for energy from 2010-2017).

biomass power plants.[15] Converted or co-firing coal power plants generally run on wood pellets, which are manufactured at wood pellet facilities and shipped to power plants globally.[16] The transition to generating electricity by burning wood is particularly concerning given the scale of potential demand and pressure on forests to meet renewable energy targets.[17]

Wood also fuels other energy and heat generation systems, including residential heating equipment, and industrial, commercial, and institutional boilers.[18] These systems are problematic for public health and the climate. In 2017, biomass and wood combustion in residential and commercial buildings, industrial boilers, and other industry sources, had greater adverse health impacts in the United States than coal combustion for electricity generation.[19]

BECCS combines bioenergy with technology to capture and store the carbon emitted at combustion.[20] BECCS is considered a carbon-removal strategy.[21] Although BECCS is not yet deployable at scale, scientific models of emission-reduction pathways that would stay within the Paris Agreement's temperature-limiting goals of 1.5ºC or 2ºC often rely on BECCS.[22] The IPCC notes that 1.5ºC-consistent pathways generally assume BECCS (including but not limited to BECCS associated with forest bioenergy and woody feedstocks) would remove 3–7 billion metric tons of CO_2 ($GtCO_2$) annually by 2050.[23] For reference, in 2019 the United States emitted over 5 billion tons of CO_2.[24] Despite these models, BECCS is not necessary to achieve the Paris Agreement's goals. The IPCC's 2018 *Special*

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[15] *See id.* at 16–17 figs. 6&7 (measuring E.U. member states' consumption of biomass at former coal power plants from 2010-2017).

[16] *Id.* at 10.

[17] *See id.* at 18-19 fig.8 (estimating EU's potential biomass consumption increases through coal-to-biomass substitutions).

[18] Christopher D. Ahlers, *Wood Burning, Biomass, Air Pollution, and Climate Change,* 46 ENV'T L. J. 49, 51, (2016).

[19] *See* Jonathan J. Buonocore, et al., *A Decade of the U.S. Energy Mix Transitioning Away from Coal: Historical Reconstruction of the Reductions in the Public Health Burden of Energy*, ENV'T RSCH. LETTERS, May 2021, at 1, 16–17 (discussing biomass' contributions through negative health impacts and mortality rates); *See also* Christopher D. Ahlers, *supra* note 18, at 51, 75-77 (outlining the ways that wood-burning emissions present health-related challenges).

[20] *See* CHRISTOPHER CONSOLI, GLOBAL CCS INSTITUTE, BIOENERGY AND CARBON CAPTURE AND STORAGE 3–4 (2019) (illustrating the process of generating bioenergy and carbon capture and storage).

[21] *Id.* at 3.

[22] *Id.*

[23] Joeri Rogelj et al., *Chapter 2: Mitigation Pathways Compatible with 1.5℃ in the Context of Sustainable Development*, *in* GLOB. WARMING OF 1.5°C 93, 129 tbl. 2.5 (Valérie Masson-Delmotte et al. eds., 2018).

[24] *Inventory of U.S. Greenhouse Gas Emissions and Sinks*, EPA, https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks (last visited Nov. 19, 2021).

Report on 1.5ºC highlights a 1.5ºC-compatible mitigation scenario without BECCS deployment.[25] The policy scenario instead relies on low energy demand pathways, including energy efficiency measures and afforestation (planting new trees), among other strategies.[26]

II. TEN YEARS OR LESS TO CURB WARMING

Effective climate change mitigation requires addressing both long-term climate stabilization and near-term risk reduction.[27] Deep cuts to greenhouse gas (GHG) emissions by 2030, on the way to net-zero CO_2 emissions, are necessary to stay within the 1.5ºC threshold.[28] This includes reducing CO_2 and more potent short-lived climate pollutants: methane, black carbon, hydrofluorocarbons, and tropospheric ozone.[29] Parallel efforts to protect forests and other carbon sinks are designed to maximize carbon stored and minimize the release of carbon to the atmosphere.[30] Allowing existing forests to grow to their ecological potential, a strategy known as "proforestation," would strengthen the Earth's natural sink capacity in the next few decades.[31]

Staying within 1.5ºC of warming will minimize the life-threatening impacts of climate change. Climate change disproportionately affects historically disadvantaged and vulnerable communities.[32] Each increment of warming further impairs human health and increases the risk of heat-related

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[25] Allen et al., *supra* note 8, at 14.

[26] *See generally* Arnulf Gruber et al., *A Low Energy Demand Scenario for Meeting the 1.5 °C Target and Sustainable Development Goals Without Negative Emission Technologies*, 3 NATURE ENERGY 515 (2018) (discussing scenarios and other strategies that could majorly transform energy supply).

[27] Durwood Zaelke et al., INST. FOR GOVERNANCE & SUSTAINABLE DEV., CTR. FOR HUM. RTS. AND ENV'T., THE NEED FOR FAST NEAR-TERM CLIMATE MITIGATION TO SLOW FEEDBACKS AND TIPPING POINTS 1 (Sept. 27, 2021).

[28] Allen et al., *supra* note 8, at 12.

[29] Allen et al., *supra* note 8, at 12; *See also* Vaishali Naik & Sophie Szopa et al., *Chapter 6: Short-lived Climate Forcers*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, 6–6 (Valérie Masson-Delmotte et al. eds., 2021) (discussing targeted SLCF policies and their role in climate change mitigation ranges).

[30] Gensuo Jia & Elena Shevliakova, *Land-Climate Interactions, in* CLIMATE CHANGE AND LAND 136 (P.R. Shukla et al. eds., 2019); *see also* Monica L. Noon et al., *Mapping irrecoverable carbon in Earth's ecosystems*, 5 NATURE SUSTAINABILITY 37, 37–38 (Jan. 2022) (identifying "irrecoverable carbon reserves that are manageable, are vulnerable to disturbance and could not be recovered by 2050 if lost today.").

[31] William R. Moomaw et al., *Intact Forests in the Unites States: Proforestation Mitigates Climate Change and Serves the Greatest Good*, FRONTIERS FORESTS & GLOB. CHANGE, June 2019, at 1, 2.

[32] *E.g.*, Allen et al., *supra* note 8, at 9 (stating that disadvantaged and vulnerable populations will disproportionally feel the effects of climate change).

deaths—especially for low-income communities and communities of color.[33] The IPCC estimates that limiting warming to 1.5ºC rather than 2ºC would protect hundreds of millions of people from climate-related risks and from being pushed into poverty.[34] Communities and ecosystems have a greater ability to adapt to 1.5ºC of warming rather than 2ºC.[35]

Additionally, enhanced climate mitigation this decade will help slow self-amplifying climate feedback loops that accelerate warming and help avoid triggering irreversible climate tipping points.[36] For example, the Arctic sea ice extent is decreasing.[37] Warmer temperatures melt sea ice in the Arctic, increasing dark ocean surface exposure and decreasing the Earth's reflectivity.[38] This causes the Earth to absorb more incoming solar radiation, exacerbating warming and sea-ice melt (land-based snow and ice in the Arctic also is melting with the same consequences).[39] These feedback loops pull the Earth closer to passing tipping points that, if crossed, would irreversibly disrupt the climate system.[40] Examples of tipping points include: the melting of the Greenland and West Antarctic ice sheets, dieback of the Amazon rainforest, and large-scale thawing of permafrost.[41] Scientists also warn that a cascade of tipping points could bring about runaway warming and a far less habitable "Hothouse Earth."[42] Avoiding these tipping points must be a priority as the world works towards climate stabilization.

The science is clear; the world must meet the Paris Agreement's 1.5ºC goal. Meeting this target requires fast action this decade on the way to net-

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[33] *Id.*; *See* CLIMATE CHANGE AND SOCIAL VULNERABILITY IN THE UNITED STATES: A FOCUS ON SIX IMPACTS, EPA, 35 (Sept. 2021) (showing that minority populations and low-income communities will suffer higher rates of premature mortality due to climate-driven temperature changes).

[34] *See* Allen et al., *supra* note 8, at 22 (warning that global warming between 2ºC and 4ºC will lead to thousands of premature deaths in the United States).

[35] *Id.* at 10.

[36] Timothy Lenton et al., Comment, *Climate Tipping Points—Too Risky to Bet Against*, NATURE 592, 594 (Nov. 27, 2019).

[37] Matthew L. Druckenmiller et al., *The Arctic*, *in* STATE OF THE CLIMATE IN 2020, BULL. AM. METEOROLOGICAL SOC'Y S263, S269, S280 (Aug. 2021), https://journals.ametsoc.org/view/journals/bams/102/8/BAMS-D-21-0086.1.xml.

[38] *Id.* at S283.

[39] Rebecca Lindsey & Michon Scott, *Climate Change: Arctic Sea Ice,* CLIMATE.GOV (Sept. 28, 2021), https://www.climate.gov/news-features/understanding-climate/climate-change-minimum-arctic-sea-ice-extent; Peter Wadhams, A FAREWELL TO ICE 107–108 (2017) ("Warm air over an ice-free Arctic also causes the snowline to retreat. . . . This of the same magnitude as the sea ice negative anomaly [and]… means that snowline retreat and sea ice retreat are each adding about the same amount to global warming.").

[40] Lenton et al., *supra* note 36, at 594; *See generally* Sybren Drijfhout et al., *Catalogue of Abrupt Shifts in Intergovernmental Panel on Climate Change Climate Models*, 112 PROC. NAT'L. ACAD. SCI. E5777, E5777 (2015) (explaining "tipping elements" and their major climate effects).

[41] Lenton et al., *supra* note 36, at 592.

[42] Lenton et al., *supra* note 36, at 594; Will Steffen et al*., Trajectories of the Earth System in the Anthropocene*, 115 PROC. NAT'L ACAD. SCI. 8252, 8254 (2018), http://www.pnas.org/content/115/33/8252.

zero. This action includes improving the carbon storage capacity of forests and other carbon sinks while reducing emissions of short-lived climate pollutants.

III. HOW FOREST BIOENERGY IS INCOMPATIBLE WITH PROTECTING THE CLIMATE, BIODIVERSITY, AND COMMUNITIES

Forest bioenergy moves the world in the wrong direction and immediately adds to warming. Replacing fossil fuels with woody biomass will not reduce emissions within the time left to curb warming, and expanding such bioenergy threatens biodiversity. Relying on large-scale deployment of BECCS distracts from the urgent need to cut emissions. Additionally, the wood pellet industry and forest biomass-fired power plants increase pollution—especially in environmental justice communities.[43]

A. Burning Woody Biomass Accelerates Near-Term Warming

Burning woody biomass increases atmospheric CO_2 levels for decades.[44] Burning forest biomass for power generation emits more CO_2 per-unit of final energy than burning fossil fuels, including coal.[45] Carbon stored in woody biomass is released into the atmosphere immediately at combustion, but it takes significantly longer—generally decades—for trees to reabsorb the same amount of carbon through regrowth.[46] At the same time, removing biomass from forests decreases the carbon storage capacity of forests.[47]

Harvesting forests for biomass can negatively impact the climate for over a century. A number of studies find that it takes many decades for tree regrowth to offset enough emissions from cutting and burning trees to make forest biomass a lower-emitting energy source than fossil fuels.[48] It would take even longer for tree regrowth to completely offset the emissions from

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[43] *See* Stefan Koester & Sam Davis, *supra* note 5, at 67.

[44] *Id.* at 66.

[45] *See, e.g,* Searchinger et al., *supra* note 1 (commenting on the increased carbon dioxide expected by 2050 if wood-burning replaces fossil-fuel-burning); Michael Norton, et al., Comment, *Serious Mismatches Continue Between Science and Policy in Forest Bioenergy*, 11 GLOB. CHANGE BIOLOGY BIOENERGY: POL'Y 1256, 1259 (2019).

[46] Searchinger, *supra* note 1.

[47] *Id.* at 3.

[48] *E.g.* Thomas Buchholz, John S. Gunn, & Benktesh Sharma, *supra* note 2, at 8; Thomas Walker et al., *supra* note 2, at 147–148; Holtsmark Bjart, *Harvesting in Boreal Forests and the Biofuel Carbon Debt*, 112 CLIMATIC CHANGE 415–428 (2011).

burning woody biomass. One study found that it would take more than 40 years before emissions from generating electricity from forest thinning were less than emissions from a baseline electricity-generation scenario.[49] Another study of boreal forests estimates that it would take 190 years to make up for the combustion emissions and the forest sequestration lost from increased harvesting—even in a case where the harvested wood was converted to pellets to replace coal in a power plant.[50] Given these findings, harvesting for biomass will increase atmospheric GHG emissions and warming beyond the deadline the world has for rapidly reducing emissions and reaching net-zero.

Even bioenergy from forestry residues is not carbon neutral for many decades. Studies demonstrate that bioenergy from forest residues—residues that are leftover from other harvesting activities or thinning—results in decades-long net carbon emissions.[51] Generally, net emissions from burning forestry residues are calculated by finding the difference between carbon released via combustion and carbon released via decomposition (if residues were left in the field).[52] A study of power plants burning local forestry residue found that 41–95% of the cumulative direct emissions would count as additional carbon emissions added to the atmosphere after 10 years.[53]

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[49] Thomas Buchholz, John S. Gunn, & Benktesh Sharma, *supra* note 2, at 8. The baseline scenario represented the U.K. electricity grid mix and excluded thinning of affected forests for wood pellet production.

[50] Holtsmark, *supra* note 2, at 415.

[51] *E.g.*, Thomas Buchholz et al., *supra* note 2, at 8 ("The GHG emission parity time for all three wood supply areas combined and individually was not reached within the 40- year model period when using a 2018 and 2025 target UK grid mix emission profile as a baseline. Based on the forest carbon stock loss from thinning in comparison to the baseline without thinning, the bioenergy scenario is unlikely to reach GHG emission parity until beyond 2,060 for both electricity GHG emission baselines."); Philippe Leturcq, *GHG Displacement Factors of Harvested Wood Products: The Myth of Substitution*, SCI. REP., Nov. 27, 2020, at 1, 7, https://doi.org/10.1038/s41598-020-77527-8 (discussing GHG displacement factors of harvested wood); Mary S. Booth, *Not Carbon Neutral: Assessing the Net Emissions Impact of Residues Burned for Bioenergy*, ENV'T RSCH. LETTERS, Feb. 21, 2018, at 1, 8, https://iopscience.iop.org/article/10.1088/1748-9326/aaac88/pdf ("The model finds that for plants burning locally sourced wood residues, from 41% (extremely rapid decomposition) to 95% (very slow decomposition) of cumulative direct emissions should be counted as contributing to atmospheric carbon loading by year 10. Even by year 50 and beyond, the model shows that net emissions are a significant proportion of direct emissions for many fuels."); Holtsmark, *supra* note 2, at 415–417 (discussing the biofuel carbon debt); Jerome Langaniere et al., *Range and Uncertainties in Estimating Delays in Greenhouse Gas Mitigation Potential of Forest Bioenergy Sourced from Canadian Forests*, 9 GCB BIOENERGY 358, 362–363, 365 (2017), https://onlinelibrary.wiley.com/doi/epdf/10.1111/gcbb.12327.pdf (discussing GHG mitigation potential of forest bioenergy); Grant M. Domke et al., *Carbon Emissions Associated with the Procurement and Utilization of Forest Harvest Residues for Energy, Northern Minnesota, USA,* 36 BIOMASS & BIOENERGY 141, 147 (2011), https://www.sciencedirect.com/science/article/pii/S0961953411005502.pdf (discussing carbon emissions associated with forest harvest residues for energy).

[52] Booth, *supra* note 51, at 1, 8.

[53] *Id.*

Some proponents of bioenergy argue that if the biomass is sourced from "sustainable harvests" (i.e., harvest levels that do not outpace the forest's incremental growth), it should be considered carbon neutral.[54] But this argument essentially double-counts ongoing forest carbon uptake. As the IPCC's 2014 mitigation report notes: "If bioenergy production is to generate a net reduction in emissions, it must do so by offsetting those emissions through increased net carbon uptake of biota and soils."[55] In other words, because burning wood for energy creates a new and additional source of emissions, offsetting those emissions also requires a new and additional source of carbon sequestration.

Expanded bioenergy also would require significantly more managed tree plantations with low carbon-sink capacities.[56] Bioenergy plantations store far less carbon than natural forests, in part because young small trees sequester less carbon than mature forests.[57] Natural forests also tend to have greater carbon stocks overall, including in soils.[58] Further, considering factors that impact forest survival (such as temperature changes, pests, and fire), replanting trees may never fully offset emissions from forest bioenergy.[59]

Regardless of the source, forest bioenergy emissions risk exceeding the Paris Agreement's temperature targets in the coming decades. Policies that treat bioenergy as carbon neutral ignore timing—a crucial factor in climate mitigation.

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[54] *See, e.g.,* CAMBRIDGE UNIVERSITY, INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE [IPCC] (2014), CLIMATE CHANGE 2014: MITIGATION OF CLIMATE CHANGE CONTRIBUTION WORKING GROUP III TO THE FIFTH ASSESSMENT REPORT OF THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, at 879 (Ottmar Edenhofer et al., eds. 2014) (noting that biomass combustion is often considered climate neutral if the "bioenergy system is managed sustainably").

[55] *Id.* at 877.

[56] Moomaw et al., supra note 31, at 2.

[57] *Id.* at 5; Simon L. Lewis et al., Comment, *Regenerate Natural Forests to Store Carbon*, 568 NATURE 25, 27 (Apr. 4, 2019).

[58] *See generally* L.B. Guo & R.M. Gifford, *Soil Carbon Stocks and Land Use Change: A Meta Analysis,* 8 GLOB. CHANGE BIOLOGY 345, 349 (2002) (explaining the different soil stocks for different land uses).

[59] John D. Sterman et al., *Does Replacing Coal with Wood Lower CO2 Emissions? Dynamic Lifecycle Analysis of Wood Bioenergy*, ENV'T RSCH. LETTERS, Jan. 18, 2018, at 1, 8.

B. BECCS Will Take Decades to Remove Carbon and is Not Available at Scale

Similarly, large-scale BECCS, especially when associated with forest biomass, is not a viable carbon-removal technique in the near- or mid-term. While CO_2 removal is necessary to stay within the 1.5ºC limit on warming, BECCS will increase emissions long before reducing them.[60] Categorizing BECCS as a carbon-negative strategy likewise relies on the false assumption that bioenergy is carbon neutral, despite the slow tree regrowth and residue decomposition rates.[61] Rather, tree regrowth exceeding the carbon impact from using forest biomass for fuel would need to occur before BECCS could be considered carbon negative.[62] Thus, as the *Working Group I Contribution to the IPCC Sixth Assessment Report* confirmed, BECCS would increase carbon emissions in the initial decades of its operation.[63]

The carbon-removal efficiency of BECCS varies and may be less than 50% due to leaks occurring before the carbon is stored in the ground.[64] If a BECCS facility burned wood pellets, a significant amount of carbon could be emitted along the supply chain and would not be captured by the CCS technology.[65] This means that tree regrowth would need to account for these inefficiencies before BECCS could be considered carbon negative.

Additionally, CCS technology is not yet deployable at scale.[66] One study estimated that the rate of carbon capture would need to increase 100 times from 2018 levels by 2050 to meet the 2ºC target.[67] For BECCS specifically, there were only five BECCS facilities in operation in 2019, collectively

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[60] EUROPEAN ACADS. SCI. ADVISORY COUNCIL, *supra* note 1, at 6–7.

[61] *Id.* at 7.

[62] *See generally id.* at 2 (explaining that reabsorbed carbon through regrowth is not happening fast enough to meet the Paris Agreement's timeline).

[63] Marcos H. Costa et al., *Chapter 5: Global Carbon and Other Biogeochemical Cycles and Feedbacks*, *in* INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, ASSESSMENT REP. 6 CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS 5–108 (Valérie Masson-Delmotte et al. eds., 2021), https://www.ipcc.ch/report/ar6/wg1/#FullReport; *see also* EUROPEAN ACADS. SCI. ADVISORY COUNCIL, *supra* note 1, at 7 (forest bioenergy, carbon capture and storage, and carbon dioxide removal).

[64] EUROPEAN ACADS. SCI. ADVISORY COUNCIL, *supra* note 1, at 6.

[65] NAT. RES. DEF. COUNCIL, A BAD BIOMASS BET 3 (Oct. 2021).

[66] *See e.g.,* R. Stuart Haszeldine et al*., Negative Emissions Technologies and Carbon Capture and Storage to Achieve the Paris Agreement Commitments*, PHIL. TRANSACTIONS OF THE ROYAL SOC'Y (Apr. 2, 2018) at 1, 14, 20 (discussing emissions technology and carbon capture and storage); CONSOLI, *supra* note 20, at 5 (discussing bioenergy and carbon capture and storage); *see also* Ragnhildur Sigurdardottir & Akshat Rathi, *Startups Climeworks and Carbfix are Working Together to Store Carbon Dioxide Removed from the Air Deep Underground*, BLOOMBERG, Sept. 8, 2021 ("The plant will capture 4,000 tons of CO_2 a year, making it the largest direct-air capture facility in the world. But that only makes up for the annual emissions of about 250 U.S. residents. It's also a long way from Climeworks' original goal of capturing 1% of annual global CO_2 emissions—more than 300 million tons—by 2025. It's now targeting 500,000 tons by the end of the decade.").

[67] Haszeldine et al., *supra* note 66, at 1, 21.

capturing around 1.5 million metric tons of CO_2 per year.[68] All operating BECCS facilities are connected to ethanol-producing plants, and most of the facilities are in the United States.[69]

BECCS' high price tag is part of the problem as well. The National Academies of Sciences, Engineering, and Medicine found that the capture and storage cost of BECCS is \$70/ton of CO_2, which is higher than the cost of CCS from fossil fuel-based power plants.[70] And the high costs required to avoid the negative effects of BECCS could sharply increase the total cost to \$100-200/ton of CO_2.[71]

C. Forest Bioenergy and BECCS Threaten Biodiversity and Ecosystem Functioning

Forest bioenergy, and especially large-scale deployment of BECCS, threatens biodiversity and ecosystem functioning. As the IPCC and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services noted: "Intensive bioenergy crop production can negatively affect biodiversity and ecosystem services, including in adjacent land, freshwater and marine ecosystems through fertilizer and pesticide use or by increasing agricultural water withdrawals, thus also impacting human capacity to adapt to climate change."[72] Converting ecosystems such as natural forests to monocrops decreases local biodiversity,[73] and the invasion of non-native trees can decrease an area's carbon sequestration.[74] Even logging and thinning for bioenergy could negatively impact biodiversity and ecosystem services.[75] Removing forest residues can decrease future forest biomass

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[68] CONSOLI, *supra* note 20, at 2, 4.

[69] *Id.*

[70] NAT. ACAD. OF SCIS., ENG'G, AND MED., NEGATIVE EMISSIONS TECHS. AND RELIABLE SEQUESTRATION: A RSCH. AGENDA 11 (2019), http://nap.edu/25259.pdf.

[71] EUROPEAN ACADS. SCI. ADVISORY COUNCIL, *supra* note 1, at 7.

[72] *Id.*

[73] M. J. Swift et al., *Biodiversity and Ecosystem Services in Agricultural Landscapes—Are We Asking the Right Questions*, 104 AGRIC., ECOSYSTEMS & ENV'T 113, 121 (2004).

[74] Martin A. Nuñez et al., *Should Tree Invasions be Used in Treeless Ecosystems to Mitigate Climate Change?*, FRONTIERS IN ECOLOGY & ENV'T, 2021, at 334, 334–335.

[75] Thomas Ranius et al., *The Effects of Logging Residue Extraction for Energy on Ecosystem Services and Biodiversity: A Synthesis,* 209 J. ENVT'L MGMT. 409, 414 (2018); Johnny de Jong & Anders Dahlberg, *Impact on Species of Conservation Interest of Forest Harvesting for Bioenergy Purposes,* 383 FOREST ECOLOGY & MGMT. 37, 45–46 (2017).

growth and threaten a broad variety of species.[76] Many of the most threatened species depend on resources such as dead wood that are scarce in managed forests.[77]

D. Increasing the Reliance on Energy from Woody Biomass Could Disproportionately Harm Vulnerable Communities

Demand for woody biomass presents a health threat to communities. Like burning coal, biomass releases pollutants that harm human health, including particulate matter.[78] Because of bioenergy's serious health impacts, the American Lung Association, the American Academy of Pediatrics, and other leading public health, medical, and nursing organizations oppose the expansion of bioenergy.[79]

Although federal and state permitting processes in the U.S. require that biomass power plants stay within emissions thresholds, the regulations are not stringent or well enforced.[80] For example, in 2018, a wood-fired biomass power plant in Stockton, California, was by far the region's largest emitter of fine particulate matter.[81] A 2014 study of 88 biomass power plants found that nearly half of the power plants characterized themselves in a way to avoid stringent federal regulations.[82]

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[76] Thomas Ranius et al., *supra* note 75, at 414; Juha Siitonen, *Threatened Saproxylic Species*, *in* BIODIVERSITY IN DEAD WOOD 356, 364 (Jogeir Stokland et al. eds., 2012).

[77] Thomas Ranius et al., *supra* note 75, at 414; Johnny de Jong & Anders Dahlberg, *supra* note 75*,* at 45–46; Jürgen Bauhus et al., *How Does the Forest-based Bioeconomy Impact Forest Biodiversity?*, *in* WHAT CAN SCIENCE TELL US: TOWARDS a SUSTAINABLE EUROPEAN FOREST-BASED BIOECONOMY 67, 68 (Lauri Hetemäki et al. eds., 2017).

[78] MARY S. BOOTH, PARTNERSHIP FOR POLICY INTEGRITY, TREES, TRASH, AND TOXICS: HOW BIOMASS ENERGY HAS BECOME THE NEW COAL 16–18 (Apr. 2, 2014); Christopher D. Ahlers, *supra* note 18, at 52, 64; *See* H. CAI & M.Q. WANG, ENERGY SYSTEMS DIVISION, ARGONNE NATIONAL LABORATORY, ESTIMATION OF EMISSION FACTORS OF PARTICULATE BLACK CARBON AND ORGANIC CARBON FROM STATIONARY, MOBILE, AND NON-POINT SOURCES IN THE UNITED STATES FOR INCORPORATION INTO GREET*,* U.S. DEPT. OF ENERGY 31, tbl.15 (May 2014) (listing mean black carbon emissions from biomass-fired boilers as emitting 0.273 g/kWh compared with 0.009 g/kWh from coal-fired boilers).

[79] Letter from Allergy & Asthma Network et. al. to Senator/Representative (Sept. 13, 2016) (on file with author).

[80] BOOTH, *supra* note 78, at 19–21.

[81] *See* STOCKTON COMMUNITY EMISSIONS REDUCTION PROGRAM, SAN JOAQUIN VALLEY AIR POLLUTION CONTROL DIST., App. C-4 (Feb. 3, 2021), https://community.valleyair.org/media/2688/appendix-c.pdf (showing $PM_{2.5}$ emissions from DTE Stockton, LLC of 13.84 tons per year; listing inspection history).

[82] BOOTH, *supra* note 78, at 5.

Further, the wood pellet industry in the U.S. is perpetuating environmental injustice to support Europe's bioenergy industry.[83] Woody biomass harvest decreases biodiversity and ecosystem services in areas near wood pellet facilities.[84] The production processes release harmful air pollutants and increase noise pollution.[85] The burden of this pollution largely falls on low-income communities and communities of color.[86] According to one study, environmental justice communities (defined as low-income communities of color) are 50% more likely to have a wood pellet facility in their community than non-environmental justice communities.[87] The study also found that in North Carolina and South Carolina wood pellet facilities were sited exclusively in environmental justice communities.[88]

Lastly, large-scale deployment of BECCS would impact food and water security, which could intensify social conflicts.[89] The IPCC *Special Report on Climate Change and Land* warns that high implementation of BECCS (11.3 $GtCO_2$ yr^{-1} in 2050) could increase the population at risk of hunger by up to 150 million people.[90] The competition between food and bioenergy crops would hit low- and middle-income countries hardest, partially because of increased food prices.[91] The IPCC also found that high BECCS deployment would use enough water to alter the water cycle at the regional scale.[92]

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[83] ENV'T INTEGRITY PROJECT, *supra* note 5, at 9; Purifoy, *supra* note 5; Gruwnald, *supra* note 5; *see also* Press Release, NAACP et al., Release: Drax Facility Fined $2.5M for Major Pollution Violation (Feb.18, 2021) (discussing major pollution violation and fine) https://www.dogwoodalliance.org/2021/02/release-drax-facility-fined-2-5m-for-major-pollution-violations/.

[84] ENV'T INTEGRITY PROJECT, *supra* note 5, at 5–6; Purifoy, *supra* note 5; Grunwald, *supra* note 5.

[85] ENV'T INTEGRITY PROJECT, *supra* note 5, at 2; Press Release, NAACP et al., *supra* note 83; Purifoy, *supra* note 5.

[86] Koester, *supra* note 5, at 64, 70; Purifoy, *supra* note 5; Grunwald, *supra* note 5.

[87] Koester, *supra* note 5, at 70.

[88] *Id.* at 68.

[89] IPBES, *supra* note 4, at 18.

[90] Intergovernmental Panel on Climate Change [IPCC], The Climate Change and Land: Summary for Policymakers, at 27 (Valérie Masson-Delmotte et al. 2020).

[91] Tomoko Hasegawa, *Food Security Under High Bioenergy Demand Toward Long-Term Climate Goals*, 163 CLIMATIC CHANGE 1587, 1598 (2020).

[92] Marcos H. Costa et al., *Chapter 5: Global Carbon and Other Biogeochemical Cycles and Feedbacks*, *in* INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, ASSESSMENT REP. 6 CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS 5–30, Cross-Chapter Box 5.1 (Valérie Masson-Delmotte et al. eds., 2021), https://www.ipcc.ch/report/ar6/wg1/#FullReport.

IV. CASE STUDY: THE EUROPEAN UNION'S TREATMENT OF WOODY BIOMASS AS A CARBON-NEUTRAL ENERGY SOURCE

The European Union (EU) categorizes forest biomass as a renewable energy source in its Renewable Energy Directive (RED) and Emissions Trading System.[93] This classification makes bioenergy eligible for renewable energy subsidies, resulting in more than €17 billion in subsidies for bioenergy in 2019 alone.[94] This endorsement of bioenergy has occurred against the warnings of the EU's own scientists and at the expense of the EU's forests.[95] Understanding the shortcomings of the EU's policies can help other governments avoid subsidizing bioenergy instead of low-carbon energy sources and forest protection.

A. History of Forest Biomass in the Renewable Energy Directive

Since 2009, the EU has included forest biomass as a carbon-neutral energy source in the RED because the European Commission transposed international carbon reporting methods into energy policy. Under IPCC and United Nations Framework Convention on Climate Change (UNFCCC) guidelines for greenhouse gas inventories, countries report the forest carbon loss at the moment of harvest.[96] To avoid double counting, the carbon emissions are counted as zero in the energy sector when biomass is burned for energy.[97] From an accounting standpoint, the harvest and use of biomass for energy decreases the EU's land sink (if harvested in the EU), but it does not affect the EU's energy sector emissions.[98]

Thus, the EU's accounting practice has encouraged treating forest bioenergy as if it actually is carbon-neutral despite its massive CO_2 footprint.[99] The RED assumes zero combustion emissions of CO_2 for forest biomass; it requires only that biomass-fired plants report the CO_2 from fossil

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[93] EUROPEAN COMMISSION, STUDY ON ENERGY SUBSIDIES AND OTHER GOVERNMENT INTERVENTIONS IN THE EUROPEAN UNION 35 (2021).

[94] *Id.* (quantifying subsidies for all bioenergy, including biomass and biofuels).

[95] Norton et al., *supra* note 45, at 1258.

[96] INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, 2006 IPCC GUIDELINES FOR NATIONAL GREENHOUSE GAS INVENTORIES, ch. 2, at 2.33 (Simon Eggleston et al., eds., 2006) ("Emissions of CO_2 from biomass fuels are estimated and reported in the AFOLU sector as part of the AFOLU methodology. In the reporting tables, emissions from combustion of biofuels are reported as information items but not included in the sectoral or national totals to avoid double counting."); *see also* Andrea Camia et al., Joint Rsch. Ctr*., JRC Science for Policy Report: The Use of Woody Biomass for Energy Production in the EU*, at 86, EUR 30548 EN (2021).

[97] GUIDELINS FOR NATIONAL GREENHOUSE GAS INVENTORIES, *supra* note 96, at 2.33; *see also* Camia et al., supra note 97, at 86.

[98] Camia et al., *supra* note 96, at 86.

[99] Norton et al., *supra* note 45, at 1257.

fuels burned during harvesting, processing, and transport of biomass, as well as non-CO_2 GHGs from biomass combustion.[100] With this policy, a power plant can switch from coal to woody biomass and claim that it has drastically reduced emissions while continuing to release similar amounts of CO_2.

B. Impacts of Classifying Forest Biomass as Renewable

Given this accounting trick, bioenergy use has increased since passage of the RED.[101] Bioenergy accounts for around 60% of "renewable" energy in the EU.[102] About half of woody biomass in the EU comes from primary biomass sources.[103] These sources include stemwood, treetops, and branches.[104] The result is an increase in emissions.[105] In 2015, the burning of forest biomass emitted 330–380 metric tons of CO_2, which researchers estimate is around 100 metric tons more than would have been emitted by the fossil fuels that bioenergy replaced.[106]

Additionally, increased bioenergy use is likely escalating forest harvest levels.[107] Using satellite data, one study showed a significant increase in harvested areas in the EU between 2015 and 2018, as compared to the preceding years.[108] Although no longer a part of the EU, the U.K.'s demand for wood pellets is damaging forests in the Southeastern U.S. because most of the U.K.'s wood pellets are imported from the U.S.[109] A 2019 study of proposed coal-to-biomass power plants in the EU estimated that 270,000 hectares of forest in the U.S. South would need to be harvested each year if all of the converted power plants sourced wood pellets from that region.[110]

The EU's own scientists oppose the RED's treatment of biomass as a carbon-neutral energy source.[111] The European Academies' Science

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[100] Council Directive 2018/2001, *supra* note 9, at 185.

[101] Camia et al., *supra* note 96, at 44; Norton et al., *supra* note 45, at 1257.

[102] Camia et al., *supra* note 96, at 40.

[103] *Id.* at 6–7.

[104] *Id.*

[105] *Id.*

[106] *Id.* at 88, Box 2.

[107] *Id.* at 53.

[108] Guido Ceccherini et al., Matters Arising, *Reply to Wernick, I.K. et al.; Palahí, M. et al.*, NATURE, Apr. 28, 2021, at E13, E18–E23; Guido Ceccherini et al., *Abrupt Increase in Harvested Forest Area Over Europe After 2015*, NATURE, July 2, 2020, at 72, 76.

[109] NAT. RES. DEF. COUNCIL, DOGWOOD ALL., and S. ENV'T L. CTR., GLOBAL MARKETS FOR BIOMASS ENERGY ARE DEVASTATING U.S. FORESTS 3 (2019).

[110] MOORE & KASPRZAK, *supra* note 14, at 27.

[111] Norton et al., *supra* note 45, at 1258.

Advisory Council (EASAC) published a paper in 2019 concluding that the EU's bioenergy policies and subsidies risk "exacerbating rather than mitigating climate change."[112] EASAC recommended that biomass should not be considered renewable unless it can be proven that replacing fossil fuels with biomass will lead to net reductions in atmospheric CO_2 within a decade.[113] In a separate commentary, EASAC warned against reliance on BECCS because of "substantial risks and uncertainties, both over its environmental impact and ability to achieve net removal of CO_2 from the atmosphere."[114]

C. 2021 Proposal to Amend the Renewable Energy Directive

Rather than heeding the advice of its scientists, the European Commission's 2021 proposal to amend the RED continues to classify forest biomass as a renewable energy source.[115] While the proposal would end subsidies for electricity-only biomass power plants in 2027,[116] critics note that this will have little impact.[117] The provision would not apply to heat and power plants.[118] It also includes a loophole that would exclude coal regions—target areas for subsidies for coal-to-biomass conversion projects.[119]

Furthermore, the proposal anticipates an increase in bioenergy. The Commission's Impact Assessment Report for the proposal anticipates that bioenergy demand will grow by 69% between 2030 and 2050.[120] This growth includes anticipated increased demand for electricity from biomass as electrification accelerates.[121]

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[112] *Id.*

[113] *Id.* at 1260.

[114] EUROPEAN ACADS. SCI. ADVISORY COUNCIL, *supra* note 1, at 2.

[115] Commission Proposal for a Directive of the European Parliament and of the Council of 7 July 2021 on Amending Directive (EU) 2018/2001, at 30–31, COM (2021) 557 final (July 14, 2021) [hereinafter Commission Proposal].

[116] *Id.* at 29–30.

[117] *See* NGO Position Paper: *To Protect Nature and the Climate, We Must Reform how Bioenergy is Treated in the EU's Renewable Energy Directive* 2 (Oct. 2021), https://www.fern.org/fileadmin/uploads/fern/Documents/2021/RED_-_NGO_Position_Paper__1_.pdf [hereinafter NGO Position Paper]; *see also What Does "Fit for 55" Mean for Forests*, FERN 2 (2021), https://www.fern.org/fileadmin/uploads/fern/Documents/2021/Fit_for_55_response.pdf (discussing how the phaseout of subsidies should not exclude coal regions).

[118] Commission Proposal, *supra* note 115, at 29–30; *see also* NGO Position Paper, *supra* note 117.

[119] Commission Proposal, *supra* note 115, at 29–30; *see also* NGO Position Paper, *supra* note 117.

[120] European Commission Staff Working Document: Impact Assessment Report, at 141-42, SWD (2021) 621 final (July 14, 2021).

[121] *Id.* at 142.

The RED's path dependence underscores the importance of excluding forest bioenergy from renewable energy policies at the outset. Categorizing biomass as a renewable source results in considerable stakeholder lock-in, making it difficult for the scientific arguments to prevail.[122] Rather than fixing the misclassification, the EU continues to prop up a heavily polluting industry and make peripheral changes at the expense of the climate.[123] By the time the EU excludes bioenergy from its renewable energy programs, enormous resources that could go towards deployment of low-emissions energy will be lost.

V. EXAMINATION OF OTHER BIOENERGY POLICIES

Countries around the world are at a pivotal moment as they transition their energy systems away from fossil fuels. As the world's largest emitters, the United States' and China's choices for transitioning their energy systems play an outsized role in whether warming stays below 1.5ºC.[124] While neither country relies on forest bioenergy to the same extent as the EU, both have taken steps to include forest biomass in their renewable energy policies.[125] Additionally, country-specific studies incorporate BECCS as a carbon removal strategy for achieving net-zero emissions by mid-century.[126] To

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[122] *See* Norton et al., *supra* note 45, at 1258 (arguing that the large investments made in biomass energy have influenced policy making by the European Parliament).

[123] *See generally* MATTHEW SMITH, TYCHO SMIT, & ANN GARDINER, TRINOMICS, FINANCIAL SUPPORT FOR ELECTRICITY GENERATION & CHP FROM SOLID BIOMASS 15 (2019) (analyzing the scope of subsidies for biomass in EU countries) http://trinomics.eu/wp-content/uploads/2019/11/Trinomics-EU-biomass-subsidies-final-report-28nov2019.pdf; FERN, *supra* note 120, at 2.

[124] *See Global Emissions*, CTR. FOR CLIMATE & ENERGY SOLUTIONS, https://www.c2es.org/content/international-emissions/ (inferring the impacts of the three main GHG producers if each were to reduce GHG emissions with energy system transitions) (last visited Nov. 17, 2021); *see also* Brady Dennis et al., *U.S. and China Issue Joint Pledge to Slow Climate Change*, WASH. POST (Nov. 10, 2021), https://www.washingtonpost.com/climate-environment/2021/11/10/us-china-declaration-climate/ (discussing pledge between United States and Chine to reduce GHGs by encouraging processes like clean energy).

[125] EPA, Policy Statement, EPA'S TREATMENT OF BIOGENIC CARBON DIOXIDE (CO_2) EMISSIONS FROM STATIONARY SOURCES THAT USE FOREST BIOMASS FOR ENERGY PRODUCTION (2018); National People's Congress of China, *Outline of the 11th Five-Year Plan on National Economic and Social Development* (2006–2010) (2006).

[126] *E.g.* Jay Fuhrman et al., *The Role of Negative Emissions in Meeting China's 2060 Carbon Neutral Goal*, OXFORD OPEN CLIMATE CHANGE, MAY 26, 2021, at 8 (contending that large-scale adoption of BECCS in China is necessary to meet the Paris Agreement's 1.5ºC target); Ciaofan Xing et al., *Spatially*

meet the goals of the Paris Agreement, protect communities, and conserve biodiversity, China and the U.S. must not follow the example of the EU by fully embracing forest bioenergy as a renewable resource.

A. The United States

The U.S. Congress continues to promote forest bioenergy as a renewable energy source.[127] From 2017 to 2020, Congress passed annual budget riders that include identical provisions categorizing bioenergy as a carbon neutral energy source.[128] The riders direct executive agencies to develop policies that "reflect the carbon-neutrality of forest bioenergy and recognize biomass as a renewable energy source, provided the use of forest biomass for energy production does not cause conversion of forests to non-forest use."[129]

Proposed language for the fiscal year 2022 spending bill would change the language slightly. Rather than encouraging policies reflecting the "carbon-neutrality of forest bioenergy," the bill would direct agencies to develop policies that "reflect the extent of the carbon benefits from forest bioenergy."[130] The draft language retains the reference to forest bioenergy as renewable.[131]

In April 2018, in response to the budget rider, the Environmental Protection Agency (EPA) issued a policy statement classifying forest

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Explicit Analysis Identifies Significant Potential for Bioenergy with Carbon Capture and Storage in China, NATURE COMMC'NS (May 26, 2021), at 1, 7 (contending that BECCS is necessary to reach China's emissions reduction goal); U. S. DEP'T STATE & U. S. EXEC. OFF. PRESIDENT, THE LONG-TERM STRATEGY OF THE UNITED STATES: PATHWAYS TO NET-ZERO GREENHOUSE GAS EMISSIONS 47 (Nov. 2021) (contending that biomass is a key component of efforts to decarbonize the energy sector).

[127] Consolidated Appropriations Act, H.R. 133, 116th Cong. § 439 (2020) (enacted).

[128] Consolidated Appropriations Act, H.R. 133, 116th Cong. § 439 (2) (2020); Consolidated Appropriations Act, 2017, Pub. L. 115-31, 131 Stat. 501 § 428; Consolidated Appropriations Act, 2018, Pub. L. No. 115-141, 132 Stat. 348, § 431(2)(a); Consolidated Appropriations Act, 2019, Pub. L. No. 116-6, 133 Stat. 265, § 428; Further Consolidated Appropriations Act, 2020, Pub. L. 116-94, 133 Stat. 2752 § 440.

[129] Further Consolidated Appropriations Act, 2020, Pub. L. 116-94, 133 Stat. 2752 § 440(2)(A).

[130] S. COMM. ON APPROPRIATIONS, 117TH CONG., MAKING APPROPRIATIONS FOR THE DEPARTMENT OF THE INTERIOR, ENVIRONMENT, AND RELATED AGENCIES FOR FISCAL YEAR ENDING SEPTEMBER 30, 2022, AND FOR OTHER PURPOSES 173–174 (Comm. Print 2021); H. COMM. ON APPROPRIATIONS, 117TH CONG., MAKING APPROPRIATIONS FOR THE DEPARTMENT OF THE INTERIOR, ENVIRONMENT, AND RELATED AGENCIES FOR FISCAL YEAR ENDING SEPTEMBER 30, 2022, AND FOR OTHER PURPOSES 166 (Comm. Print 2021); Marc Heller, *Biomass Loses 'Carbon Neutral' Crown in Senate Spending Bill*, E&E News (Oct. 20, 2021).

[131] S. COMM. ON APPROPRIATIONS, 117TH CONG., MAKING APPROPRIATIONS FOR THE DEPARTMENT OF THE INTERIOR, ENVIRONMENT, AND RELATED AGENCIES FOR FISCAL YEAR ENDING SEPTEMBER 30, 2022, AND FOR OTHER PURPOSES 173–174 (Comm. Print 2021); H. COMM. ON APPROPRIATIONS, 117TH CONG., MAKING APPROPRIATIONS FOR THE DEPARTMENT OF THE INTERIOR, ENVIRONMENT, AND RELATED AGENCIES FOR FISCAL YEAR ENDING SEPTEMBER 30, 2022, AND FOR OTHER PURPOSES 166–167 (Comm. Print 2021); *see also* Marc Heller, *supra* note 130.

biomass as carbon neutral.[132] But the EPA has yet to include this statement in a formally promulgated regulation. The Biden administration withdrew a proposed rule, drafted by the Trump administration, before it was published in the Federal Register.[133] The Biden administration has not issued a statement regarding forest bioenergy's emissions.

In November 2021, Congress passed the Infrastructure Investment and Jobs Act (H.R. 3684), which promotes BECCS with woody biomass,[134] provides funding for biomass use,[135] and encourages agencies to use biomass to develop "clean hydrogen."[136] The Act provides $12 million in annual funding from 2022 to 2026 for the use of woody biomass from federal forests.[137] The Act also allocates $400 million for wood product facilities that use byproducts from ecosystem restoration—funding that could ultimately go to wood pellet facilities.[138]

Policy projections indicate that bioenergy use will increase if the U.S. stays on its current policy course.[139] In November 2021, the U.S. released its long-term strategy to reach net-zero GHG emissions.[140] The strategy refers to biomass as "carbon-beneficial"[141] but includes language emphasizing the need to ensure that large-scale biomass use results in actual emission

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[132] EPA, EPA'S TREATMENT OF BIOGENIC CARBON DIOXIDE (CO_2) EMISSIONS FROM STATIONARY SOURCES THAT USE FOREST BIOMASS FOR ENERGY PRODUCTION 1 (2019), https://www.epa.gov/sites/production/files/2018-04/documents/biomass_policy_statement_2018_04_23.pdf.

[133] Stephen Lee, *Scientists Fear Trump Wood-Burn Stance to Stay Under Regan EPA,* BLOOMBERG L. (Apr. 12, 2021) https://news.bloomberglaw.com/environment-and-energy/scientists-fear-trump-wood-burn-stance-to-stay-under-regan-epa.

[134] Infrastructure Investment and Jobs Act, H.R. 3684, 117th Cong. § 80402 (2021) (enacted); *see also* Letter from William R. Moomaw, Emeritus Professor, The Fletcher School, et al. to President Biden and Members of Congress (Nov. 4, 2021), https://johnmuirproject.org/wp-content/uploads/2021/11/ScientistLetterOpposingLoggingProvisionsInBBB_BIF4Nov21.pdf.

[135] Infrastructure Investment and Jobs Act, H.R. 3684, 117th Cong. Title VI § 614 (2021) (subsection on National Forest System) (enacted); *see also* Letter from William R. Moomaw, *supra* note 134.

[136] Infrastructure Investment and Jobs Act, H.R. 3684, 117th Cong. § 814 (2021) (enacted).

[137] Infrastructure Investment and Jobs Act, H.R. 3684, 117th Cong. Title VI § 614 (2021) (subsection on National Forest System) (enacted).

[138] Infrastructure Investment and Jobs Act, H.R. 3684, 117th Cong. § 40804(b)(3) (2021) (enacted); *see also* Letter from William R. Moomaw, *supra* note 134.

[139] U.S. DEP'T STATE & U. S. EXEC. OFF. PRESIDENT, THE LONG-TERM STRATEGY OF THE UNITED STATES: PATHWAYS TO NET-ZERO GREENHOUSE GAS EMISSIONS 47 (Nov. 2021).

[140] *See generally* U.S. DEP'T STATE & U. S. EXEC. OFF. PRESIDENT, THE LONG-TERM STRATEGY OF THE UNITED STATES: PATHWAYS TO NET-ZERO GREENHOUSE GAS EMISSIONS (Nov. 2021).

[141] *Id.* at 46.

reductions and reflects consideration of non-carbon consequences.[142] Still, the strategy states that "biomass is a key component of efforts to decarbonize the energy sector."[143] The strategy projects that biomass use, both with and without CCS, will increase in electricity generation[144] and the industrial sector[145] through 2050. Additionally, in the 2021 Annual Energy Outlook, the U.S. Energy Information Administration projected biomass energy production would increase to 5.39 quadrillion British thermal unit (Btu) by 2050 from 4.47 quadrillion Btu in 2020.

At the state level, bioenergy accounts for a significant share of some states' energy portfolios. According to an industry trade publication, in January 2022, California alone had 530 megawatts (MW) of capacity from wood and wood-derived biomass power plants.[146] This compares to the combined capacity of New England and New York at 491 MW.[147] In Maine, biomass generates 20% of the State's total net generation, the largest share of any state.[148] In Vermont, where nearly all in-state electricity generation comes from "renewable" resources, biomass accounts for 17% of the total net generation.[149] In New Hampshire, biomass supplied about 6% of the total net generation in 2020.[150]

State renewable energy policies generally treat forest biomass as renewable and incentivize its use. Nearly all of the states that have renewable portfolio standards (RPS) or renewable energy standards include forest bioenergy under their definition of "renewable energy resource."[151]

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[142] *Id.* at 47.

[143] *Id.* (contending that biomass is a key component of efforts to decarbonize the energy sector).

[144] *Id.* at 26 (Figure 5).

[145] *Id.* at 34 (Figure 10).

[146] *U.S. Biomass Power Plants*, BIOMASS MAGAZINE (Jan. 18, 2022), http://biomassmagazine.com/plants/listplants/biomass/US/ (calculating biomass power by adding capacities with feedstocks of woody biomass, logging, mill residue, wood residuals, urban wood waste, orchard removal trees, forest thinning, and wood waste).

[147] *Id.* (classifying Vermont, New Hampshire, Maine, Massachusetts, Rhode Island and Connecticut as New England states).

[148] *Maine: State Profile and Energy Estimates,* U.S. ENERGY INFO. ADMIN. (Aug. 19, 2021), https://www.eia.gov/state/analysis.php?sid=ME.

[149] *Vermont: State Profile and Energy Estimates*, U.S. ENERGY INFO. ADMIN., (Sept. 16, 2021), https://www.eia.gov/state/analysis.php?sid=VT.

[150] *New Hampshire: State Profile and Energy Estimates,* U.S. ENERGY INFO. ADMIN., (Aug. 19, 2021), https://www.eia.gov/state/analysis.php?sid=NH.

[151] *See generally, State Renewable Portfolio Standards and Goals*, NAT'L CONF. OF STATE LEGISTURES (Aug. 31, 2021), https://www.ncsl.org/research/energy/renewable-portfolio-standards.aspx (listing states with renewable portfolio standards), *see also.,* MICH. COMP. LAWS ANN. § 460.1011(g)(i) (West 2017); OR. REV. STAT. ANN. § 469A.025(2) (West 2021);. WASH. REV. CODE § 19.285.030(12)(d) (2019) (providing examples of states with renewable portfolio standards).

However, some states exclude old-growth timber from qualifying[152] or have limits on forest resources available for use.[153]

Only a few states exclude most woody biomass. Colorado passed a law in 2021 requiring that biomass must be "GHG neutral" within five years to be eligible as a renewable resource.[154] In March 2020, Virginia passed the Clean Economy Act, which requires Virginia's power producers to reduce their emissions to zero by 2050 and transition to clean energy.[155] The Act excludes woody biomass from its definition of eligible sources for Virginia's RPS and defines "zero-carbon electricity" as "electricity generated by any generating unit that does not emit carbon dioxide as a by-product of combusting fuel to generate electricity."[156] The Act includes one exception for biomass facilities that provide less than 10% of their electrical generation to the grid, but the Act caps the number of credits that may be sold for those facilities.[157] The Act also requires that all existing stand-alone biomass plants permanently retire by 2028 and that all carbon-emitting power plants close by 2045 (which includes coal and biomass co-firing plants).[158]

Other states have been struggling with how to treat biomass. In its 2018 Clean Energy Plan, North Carolina emphasized the harmful climate impacts of the wood pellet industry in North Carolina.[159] At the same time, electricity generation from biomass is eligible for renewable energy credits in North Carolina.[160] And in 2019, North Carolina approved a permit for the expansion of the Enviva wood pellet plant.[161] In Massachusetts, the government enacted regulations in 2012 that took large-scale, low-efficiency

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[152] *See* MD. CODE ANN., PUB. UTIL. § 7-701(h), (l)(1)(i) (West 2021) (excluding old-growth forests from qualifying as biomass); WASH. REV. CODE §19.285.30(3)(b), (12)(d) (2019) (limiting the definition of biomass energy as it relates to eligible renewable resources).

[153] *E.g.*, N.M. STAT. § 62-16-3(H)(3) (2019) (limiting the resources that qualify as biomass).

[154] COLO. REV. STAT. ANN. § 40-2-124(1)(a)(IV).

[155] S.B. 851, 2020 General Assemb. (Va. 2020).

[156] *Id.*

[157] *Id.*

[158] *Id.*

[160] N. C. DEP'T ENV'T QUALITY, CLEAN ENERGY PLAN: TRANSITIONING TO A 21ST CENTURY ELECTRICITY SYSTEM 25–26 (Oct. 2019).

[161] N.C. General Statute § 62-133.8(a)(8); Lisa Sorg, *North Carolina Sends Conflicting Messages on Burning Wood as Fuel*, NC POL'Y WATCH (Oct. 2, 2019), http://www.ncpolicywatch.com/2019/10/02/north-carolina-sends-conflicting-messages-on-burning-wood-as-fuel/.

biomass plants out of the state's renewable energy portfolio.[162] This rule change is now under threat, however, as the current administration in Massachusetts has proposed significant rollbacks of environmental protections.[163]

B. China

Multiple statutes in China address bioenergy. China's Renewable Energy Law includes bioenergy within the broader category of renewable energy (also referred to as non-fossil fuel energy).[164] The Renewable Energy Law establishes the national legislative framework to promote the development and deployment of bioenergy.[165] China's Energy Conservation Law also reiterates support for bioenergy.[166]

Additionally, China's Five-Year planning system has set increasingly ambitious targets for non-fossil fuel energy, including bioenergy. Such targets have significant implications for China's social and economic development policies. Starting in the 11th Five-Year period (2006–2010), the Five-Year plans have included the development and deployment of bioenergy.[167] China's current targets include an aim to increase the

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[162] 225 MASS. CODE REGS. 14.00 (2021); *see also* Mary S. Booth and Margaret Sheehan, *Closing the Biomass Carbon Loophole,* COMMONWEALTH MAG. (Oct. 11, 2012).

[163] *See* Mary S. Booth, *Get Ready for Another Biomass Battle,* COMMONWEALTH MAG. (May 14, 2019).

[164] Kezaisheng Nengyuan Fa (可再生能源法) [Renewable Energy Law] (promulgated by the Standing Comm. Nat'l People's Cong., Feb. 28, 2005, amended by the Standing Comm. Nat'l People's Cong., Dec. 26, 2009, effective Jan. 1, 2006), art. 2, (China) http://www.npc.gov.cn/zgrdw/huiyi/cwh/1112/2009-12/26/content_1533216.htm.

[165] *Id.*

[166] Jieyue Nengyuan Fa (节约能源法) [Energy Conservation Law] (promulgated by the Standing Comm. Nat'l People's Cong., Nov. 1, 1997, amended by the Standing Comm. Nat'l People's Cong., Oct. 28, 2007, July 2, 2016 & Oct. 26, 2018, effective Apr. 1, 2008), art. 58, (China) http://www.npc.gov.cn/zgrdw/npc/xinwen/2018-11/05/content_2065665.htm.

[167] *Outline of the 11th Five-Year Plan on National Economic and Social Development of the People's Republic of China*, TENTH NAT'L PEOPLE'S CONG., CHINA (2006), http://www.gov.cn/gongbao/content/2006/content_268766.htm.

percentage of non- fossil fuels to around 20% of total energy consumption by 2025,[168] 25% by 2030,[169] and eventually to over 80% by 2060.[170]

A recently released national policy document further elaborates on China's actions to promote renewable energy.[171] This includes a policy that renewable energy consumption will not count towards the total energy consumption limits for localities.[172] Such policies link closely to China's strategic priorities for achieving its climate goals of reaching carbon peaking before 2030 and carbon neutrality before 2060.[173] Although the current scale of bioenergy deployment in China is limited, the Chinese government has issued numerous policies providing financial incentives, including subsidies, for biomass power generation.[174] For 2021, China's national government allocated 2.5 billion RMB (approximately 390 million USD) to subsidize the

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[168] *Outline of the 14th Five-Year Plan for National Economic and Social Development and the Long-Range Objectives Through the Year 2035*, Thirteenth Nat'l People's Cong. China (2021), https://www.ndrc.gov.cn/xxgk/zcfb/ghwb/202103/t20210323_1270124.html?code=&state=123.

[169] H.E. Xi Jinping, President of the People's Republic of China, Remarks by Chinese President Xi Jinping at Climate Ambition Summit (Dec. 12, 2020), http://www.xinhuanet.com/english/2020-12/12/c_139584803.htm.

[170] *China's Mid-Century Long-Term Low Greenhouse Gas Emission Development Strategy*, China, 8–9 (Oct. 28, 2021), https://unfccc.int/sites/default/files/resource/China%E2%80%99s%20Mid-Century%20Long-Term%20Low%20Greenhouse%20Gas%20Emission%20Development%20Strategy.pdf; *See also Ahead of COP 26, China Submits Update to NDC and Mid-Century Development Strategy*, Inst. for Governance & Sustainable Dev. (Oct. 28, 2021), https://www.igsd.org/ahead-of-cop-26-china-submits-update-to-ndc-and-mid-century-development-strategy/ (explaining China's new NDC).

[171] Wanshan Nengyuan Xiaofei Qiangdu He Zongliang Shuangkong Zhidu Fang'an (完善能源消费强度和总量双控制度方案) [Systematic Plan for Improving the Dual-Control on the Intensity and Total Amount of Energy Consumption] (promulgated by China National Development and Reform Commission, Sept. 11, 2021, effective Sept. 11, 2021)(China), http://www.gov.cn/zhengce/zhengceku/2021-09/17/content_5637960.htm.

[172] *Id.*

[173] H.E. Xi Jinping, *supra* note 169.

[174] *See, e.g.,* Guanyu Fazhan Shengwu Nengyuan He Shengwu Huagong Caishui Fuchi Zhengce De Shishi Yijian (关于发展生物能源和生物化工财税扶持政策的实施意见) [Implementation Opinions on the Financial and Tax Policies for Supporting the Development of Bioenergy and Biochemistry] (promulgated by China Ministry of Finance, National Development and Reform Commission, Ministry of Agriculture, State Taxation Administration and National Forestry Administration, Sept. 30, 2006, effective Sept. 30, 2006), http://www.chinatax.gov.cn/chinatax/n810341/n810765/n812183/200611/c1196178/content.html.

operation of biomass power stations.[175] The 2021 policy differentiates between regions and ultimately could provide more financial incentives for certain less-developed and environmentally sensitive regions to undertake forest bioenergy projects.[176]

Additionally, the Chinese government intended to expand bioenergy plantations to support its renewable energy push. The government announced the goal of developing 16.78 million hectares of energy forests (an area about the size of Belgium) by 2020.[177] This goal included 10.1 million hectares of new forests and 6.77 million hectares to be converted from existing forests.[178]

VI. CALLS TO ACTION

Before it is too late, governments must stop burning forests and instead promote solutions that reduce near-term risks and protect the climate, biodiversity, and communities. Investing in forest biomass and BECCS takes resources away from the urgent mitigation efforts needed to achieve countries' carbon neutrality goals, including greater protection of forests. The following is a list of policy recommendations for governments to adopt at the international, national, and subnational levels.

A. Re-evaluate Policies to Ensure Correct Accounting of Forest Bioenergy's Impacts

Governments should advance science-based renewable energy policies that reflect both accurate lifecycle accounting of energy sources' GHG emissions and the urgency of the climate crisis. First, policies and programs that incentivize renewable energy should include only those sources that have very low lifecycle emissions. Governments should not rely on nonscience-based policy assumptions regarding any source's emissions. Second, timing must be an integral part of calculating a source's net

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[175] 2021 Nian Shengwuzhi Fadian Xiangmu Jianshe Gongzuo Fangan (2021年生物质发电项目建设工作方案) [Workplan on Construction of Biomass Power Generation Projects in 2021] (promulgated by China National Development and Reform Commission, Ministry of Finance and National Energy Administration, Aug. 11, 2021, effective date Aug. 11, 2021), https://sme.miit.gov.cn/zcfg/art/2021/art_322ae7c954f8478c822bdb46fc510588.html.

[176] *Id.*

[177] National Forestry Administration (now "National Forestry and Grassland Administration"), *National Forest Bioenergy Development Plan* (2011-2020) (May 28, 2013) http://www.ccchina.org.cn/nDetail.aspx?newsId=40427&TId=60 ("By 2020, [China will] develop 16.78 million hectares of energy forests, including 10.1 million hectares of new forests and 6.77 million hectares to be converted from existing forests") (quotes were translated by authors).

[178] *Id.*

emissions. Any source that does not have very low lifecycle emissions within a decade should not qualify as renewable energy. Thus, a source that assumes negative emissions more than a decade in the future would not be considered very low emitting in the near-term.

Regarding forest bioenergy specifically, the full lifecycle emissions from harvest to combustion should be counted for each facility.[179] Regardless of other carbon accounting schemes, governments must not ignore forest bioenergy's combustion emissions, nor the other land-sector emissions associated with bioenergy use, including from soil carbon loss and biomass burned during pellet manufacturing. Because forest bioenergy increases net GHG emissions for decades to centuries, it should be excluded from renewable energy and non-fossil fuel energy programs.

For greatest impact, national and subnational governments both should take these actions. For example, if the U.S. Congress were to pass clean energy legislation that excluded forest bioenergy, the law would be an important step in curbing forest bioenergy's growth. But each state's renewable energy policies and subsidies might limit the impact of federal legislation. To phase out forest bioenergy, governments at both levels need to act.

In terms of BECCS, countries' emissions-reduction plans should not rely on deployment of BECCS to reach net-zero emissions. More needs to be done to ensure that timing is a central consideration of countries' mid-century strategies so that governments do not exceed their emissions goals because of reliance on CCS. Instead, countries should commit to enhancing carbon sinks and reducing CO_2 and non-CO_2 climate pollutants, including methane, hydrofluorocarbons, tropospheric ozone, and black carbon. Governments must also promote methods to reduce energy demand. By taking these steps, governments will align their renewable energy policies and non-fossil energy targets with their carbon reduction goals.

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[179] P'SHIP FOR POL'Y INTEGRITY, MARY S. BOOTH & BEN MITCHELL, *Paper Tiger: Why the EU's RED II Biomass Sustainability Criteria Fail Forests and the Climate* (Jul. 6, 2020) ("Implement full life-cycle GHG accounting: Full accounting for forest biomass includes all the GHG emitted by growing, harvesting, processing, transporting, and burning the fuel."), http://eubiomasscase.org/wp-content/uploads/2020/07/RED-II-biomass-Paper-Tiger-July-6-2020.pdf.

B. End Incentives for Forest Bioenergy and Invest in Forest Preservation, Low-emissions Energy, and Strategies to Reduce Energy Demand

Countries that subsidize or otherwise incentivize facilities that burn woody biomass must redirect those subsidies. Without these subsidies, forest bioenergy likely would not be economically feasible.[180] A study of 15 European countries found that on average 9% of all renewable energy subsidies went to solid biomass in 2015 and 2016.[181] And across these 15 countries, biomass subsidies increased from 2015 to 2017.[182] Finland allocated one-third of its total renewable energy subsidies to bioenergy in 2015.[183] Countries, including those within the EU, can immediately end subsidies for bioenergy plants. The Netherlands voted to end subsidies for new bioenergy plants in 2021 (though the existing subsidies remain in place).[184] At a time when investment in climate mitigation falls far below what is necessary,[185] these subsidies should be redirected toward low-emissions energy sources or strategies for reducing energy demand. Such incentives would be aligned with the IPCC pathway that does not rely on BECCS to stay within the 1.5ºC limit of warming.[186]

National and subnational governments also should increase investment in forest preservation and increase the percentage of forests protected from development. Proforestation—protection and enhancement of existing forests—will have a larger near-term impact on carbon sequestration than planting new trees.[187] Because of their higher growth rate, older trees can store significantly more carbon each year than younger trees.[188] Proforestation calls for governments to manage more forests as "intact"—reserved from logging and other development. This allows trees to grow to

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[180] SETH WALKER ET AL., RISI, AN ANALYSIS OF UK BIOMASS POWER POLICY, US SOUTH PELLET PRODUCTION, AND IMPACTS ON WOOD FIBER MARKET 16 (2015), https://docplayer.net/25281897-An-analysis-of-uk-biomass-power-policy-us-south-pellet-production-and-impacts-on-wood-fiber-markets-prepared-for-the-american-forest-paper.html.

[181] MATTHEW SMITH, TYCHO SMIT, & ANN GARDINER, TRINOMICS B.V., FINANCIAL SUPPORT FOR ELECTRICITY GENERATION & CHP FROM SOLID BIOMASS 19–20 (2019), http://trinomics.eu/wp-content/uploads/2019/11/Trinomics-EU-biomass-subsidies-final-report-28nov2019.pdf.

[182] *Id.* at 20, tbl. 3-1.

[183] *Id.* at 15.

[184] Justin Catanoso, *Dutch to Limit Forest Biomass Subsidies, Possibly Signaling EU Sea Change*, MONGABAY (March 9, 2021), https://news.mongabay.com/2021/03/dutch-to-limit-forest-biomass-subsidies-possibly-signaling-eu-sea-change/.

[185] Sophie Yeo, *Where Climate Cash is Flowing and Why it's not Enough,* NATURE NEWS FEATURE (Sept. 17, 2019), https://www.nature.com/articles/d41586-019-02712-3.

[186] Allen et al., *supra* note 8, Fig. SPM.3b; *see generally* Arnulf Gruber et al., *supra* note 26 (describing a low energy demand pathway).

[187] Moomaw et al., *supra* note 31, at 2.

[188] N. L. Stephenson et al., *Rate of Tree Carbon Accumulation Increases Continuously with Tree Size,* NATURE, Jan. 2014, at 90, 93; Moomaw et al., *supra* note 31, at 2.

their ecological potential.[189] But less than 20% of the world's forests, and only 7% of U.S. forests, are intact.[190] In the U.S., eastern forests have especially high carbon sequestration potential and could store significantly more carbon if protected from development.[191] Designating more existing forests as reserves, especially those with large potentials to sequester carbon, will assist near-term mitigation efforts by strengthening forests' carbon sinks.

C. Advance International Consensus on the Harms from Forest Bioenergy, Specifically the Impact on Climate and Biodiversity

At the international level, countries could commit to protect forests and end subsidies for woody biomass power plants. By signing the Glasgow Leaders' Declaration on Forests and Land Use, over 140 countries pledged to conserve forests, accelerate forest restoration, and reverse forest loss by 2030.[192] World leaders announced the Declaration at the 26th Conference of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC).[193] The signatories, including China, the E.U., and the U.S., pledged to protect over 90% of global forests.[194] The Declaration includes a commitment to "facilitate the alignment of financial flows with international goals to reverse forest loss and degradation while ensuring robust policies and systems are in place to accelerate the transition to an economy that is resilient and advances forest, sustainable land use, biodiversity and climate goals."[195]

That said, while the Declaration is an important step, it does not count logging as a deforestation activity.[196] This could leave room for countries to approve high levels of harvest in pursuit of increasing bioenergy.[197] In effect,

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[189] Moomaw et al., *supra* note 31, at 1.

[190] *Id.* at 2.

[191] *See id.* at 4–5 (discussing studies that suggest letting forests grow is the best way to sequester carbon).

[192] *Glasgow Leaders' Declaration on Forests and Land Use,* U.N. CLIMATE CHANGE CONF. U.K. 2021 (Nov. 12, 2021), https://ukcop26.org/glasgow-leaders-declaration-on-forests-and-land-use/.

[193] *Id.*

[194] *Id.*

[195] *Id.*

[196] *See The Glasgow Declaration on Forests Doesn't Go Far Enough,* FOREST DEFS. ALL. (Nov. 2, 2021), https://forestdefenders.eu/the-glasgow-declaration-on-forests-doesnt-go-far-enough/ (discussing that permanent forest loss happens when one use for land is converted into another use, which is not ultimately counted as traditional forest degradation).

[197] *Id.*

countries will contradict their commitment to the declaration by continuing to incentivize energy from woody biomass.[198] Countries should go further than the minimum required by the Declaration and preserve forests by ending reliance on, and redirecting, incentives for forest bioenergy.

Additionally, under the UNFCCC Paris Agreement, countries should commit to forest preservation, especially of existing forests with large carbon-storage potential, in their nationally determined contributions for GHG emission reductions.[199] Parties with forest bioenergy in their energy mix should ensure proper accounting of the emissions while also rapidly reducing forest bioenergy's share of energy generation. Countries should not rely on BECCS to reach their Paris Agreement commitments.

Furthermore, countries should address forest bioenergy through the Convention on Biological Diversity (CBD). Parties to the CBD adopted the Kunming Declaration at the 15th Conference of the Parties hosted by China in October 2021.[200] The Declaration includes a commitment to "reform incentive structures, eliminating, phasing out or reforming subsidies and other incentives harmful to biodiversity . . . ."[201] This commitment must encompass the elimination of incentives for forest bioenergy.

Parties to the CBD continue to negotiate the *Post-2020 Global Biodiversity Framework* and plan to meet again in China in May 2022.[202] Parties should include language in the post-2020 framework recognizing that burning woody biomass undermines biodiversity and must be phased down. The first draft of the framework includes language to redirect or eliminate incentives that are harmful to biodiversity.[203] Implementing such a commitment must encompass redirecting incentives for forest bioenergy. Additionally, rejecting woody biomass as a clean energy source fits into the draft post-2020 framework's call to better coordinate climate change targets and biodiversity conservation.[204]

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[198] *See* Justin Catanoso, *COP26: E.U. is Committed to Forest Biomass Burning to Cut Fossil Fuel Use*, MONGABAY (Nov. 10, 2021), https://news.mongabay.com/2021/11/cop26-e-u-is-committed-to-forest-biomass-burning-to-cut-fossil-fuel-use/ (explaining the contradiction between signing the Declaration and continuing to use biomass).

[199] Under the Paris Agreement, Parties are required to submit nationally determined contributions (NDCs) that explain their plans to mitigate and adapt to climate change. *See All About the NDCs,* U.N., https://www.un.org/en/climatechange/all-about-ndcs (last visited Nov. 17, 2021) (explaining the purpose of NDCs).

[200] Convention on Biological Diversity, *Kunming Declaration "Ecological Civilization: Building a Shared Future for All Life on Earth"*, U.N. Doc. CBD/COP/15/5/Add.1 (Oct. 13, 2021).

[201] *Id.* at ¶13.

[202] *Preparations for the Post-2020 Biodiversity Framework,* CONVENTION ON BIOLOGICAL DIVERSITY, https://www.cbd.int/conferences/post2020 (last visited Nov. 17, 2021).

[203] Open Ended Working Group on the Post-2020 Global Biodiversity Framework, First Draft of the Post-2020 Global Biodiversity Framework, CBD/WG2020/3/3, *Annex* ¶12 (July 5, 2021) (Target 18).

[204] *Id.* at ¶12.

Finally, over 75 countries have united as the High Ambition Coalition for Nature and People.[205] Countries in the Coalition are committed to enhancing protections for nature, including by promoting commitments to conserve 30% of lands and ocean by 2030 (30x30 pledge).[206] The Coalition works to advance its goals through myriad international channels, including both the UNFCCC and the CBD.[207] Coalition members could prioritize scaling up the areas protected as intact forests through the 30x30 pledge.

CONCLUSION

Time is running out for countries to act on climate change to avert near-term emergencies and secure long-term climate stability. The world cannot afford to burn forests in the name of climate mitigation. Governments must act now to protect communities and ecosystems by conserving forests and reducing GHG emissions.

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[205] *HAC Member Countries,* HIGH AMBITION COAL. FOR NATURE AND PEOPLE, https://www.hacfornatureandpeople.org/hac-members (last visited Nov. 17, 2021).

[206] *Launch at the One Planet Summit*, HIGH AMBITION COAL. FOR NATURE AND PEOPLE, https://www.hacfornatureandpeople.org/hac-launch-hub-page (last visited Nov. 17, 2021).

[207] *See Roadmap to 30x30*, HIGH AMBITION COAL. FOR NATURE AND PEOPLE, https://www.hacfornatureandpeople.org/roadmap (last visited Nov. 17, 2021) (highlighting the many meetings various Coalition countries had to advance their goals along different channels).