Submission by IGSD to the Global Stocktake

We submit the attached study published in the Proceedings of the National Academy of Sciences (PNAS) of the United States in May 2022 for consideration.

This study presents state-of-the-art science regarding the critical need to pair non-CO_2 mitigation with CO_2 mitigation to reduce near-term warming, thereby reducing risks associated with triggering dangerous feedbacks and crossing irreversible tipping points. The study demonstrates that *only* through a concerted, dual strategy can humanity meet the goals of the Paris Agreement.

The innovation of this study is in the framework developed to compare the impacts of CO_2-focused decarbonization mitigation with decarbonization *plus measures targeting non-CO_2* on the pace of warming over the next ten to twenty years. This requires understanding the current human contributions to warming and considering both short-lived and long-lived climate pollutants, *the sources* of and co-emission of such pollutants, *the time* needed to reduce these pollutants, and the impacts on *temperature* and *pace of warming* from strategies targeting sources of these pollutants.

The study establishes four concepts of central importance to the objectives of the Paris Agreement:

1. To "significantly reduce the risks and impacts of climate change",[1] **requires a dual strategy to both slow warming in the near term to a rate within the limits of human and natural system adaptation and limit longer-term warming later this century**.[2]
2. Achieving net-zero CO_2 emissions by mid-century is essential to limiting warming later this century; however, **efforts to cut CO_2 emissions by decarbonizing the energy system *alone* cannot keep warming below 2°C**.
3. *Staying below 1.5°C requires a dual strategy* that pairs CO_2 mitigation efforts *with* measures targeting non-CO_2 short-lived climate pollutants (SLCP—methane, hydrofluorocarbon refrigerants, black carbon soot, and ground-level ozone smog), as well as longer-lived nitrous oxide. This dual strategy will **avoid nearly five times more net warming and 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.
4. These two strategies pairing an SLCP "sprint" to slow warming in the near term with net-zero CO_2 "marathon" to limit longer-term warming are not interchangeable strategies.

The urgency of slowing warming in the near term means that speed must become the key factor in the selection of climate solutions,[3] to quickly limit warming, slow self-reinforcing feedbacks, avoid or at least delay tipping points, and protect the most vulnerable people and ecosystems.[4] Halting the destruction of our forests and other carbon sinks[5] so they continue to store carbon and do not turn into sources of CO_2 can provide additional fast mitigation, while also protecting biodiversity.[6] The United Nations Environment Programme, the Intergovernmental Panel on Climate Change (IPCC),[7] the Climate and Clean Air Coalition (CCAC),[8] and the Arctic Council[9] have all contributed to this scientific understanding. The IPCC's Working Group II report underscores the dire consequences of further delays in global action and the urgency of slowing warming in the near term.[10]

Keywords: Short-lived climate pollutant; Peer-reviewed; Overshoot; Feedbacks; Tipping Points; Non-CO_2

[1] United Nations Framework Convention on Climate Change (UNFCCC) (2016) The Paris Agreement, Article 2.1(a) ("Holding the increase in the global average temperature to well below 2 °C above preindustrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change;").

[2] United Nations (1992) United Nations Framework Convention on Climate Change, Article 2 recognizes that the objective of preventing dangerous anthropogenic interference with the climate system "should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner."

[3] 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."). *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.").

[4] 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...."); Lee J.-Y., Marotzke J., Bala G., Cao L., Corti S., Dunne J. P., Engelbrecht F., Fischer E., Fyfe J. C., Jones C., Maycock A., Mutemi J., Ndiaye O., Panickal S., & T. Zhou (2021) *Chapter 4: Future Global Climate: Scenario-Based Projections and Near-Term Information*, *in* CLIMATE CHANGE 2021: THE PHYSICAL SCIENCE BASIS, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte V., *et al.* (eds.), 4-96 (Table 4.10 lists 15 components of the Earth system susceptible to tipping points); *and* Armstrong McKay D. I., Staal A., Abrams J. F., Winkelmann R., Sakschewski B., Loriani S., Fetzer I., Cornell S. E., Rockström J., & Lenton T. M. (2022) *Exceeding 1.5°C global warming could trigger multiple climate tipping points*, SCIENCE 377(6611): eabn7950, 1–10, 7 ("The chance of triggering CTPs is already non-negligible and will grow even with stringent climate mitigation (SSP1-1.9 in Fig. 2, B and C). Nevertheless, achieving the Paris Agreement's aim to pursue efforts to limit warming to 1.5°C would clearly be safer than keeping global warming below 2°C (90) (Fig. 2). Going from 1.5 to 2°C increases the likelihood of committing to WAIS and GrIS collapse near complete warm-water coral die-off, and abrupt permafrost thaw; further, the best estimate threshold for LABC collapse is crossed. The likelihood of triggering AMOC collapse, Boreal forest shifts, and extra-polar glacier loss becomes non-negligible at >1.5°C and glacier loss becomes likely by ~2°C. A cluster of abrupt shifts occur in ESMs at 1.5 to 2°C (19). Although not tipping elements, ASSI loss could become regular by 2°C, gradual permafrost thaw would likely become widespread beyond 1.5°C, and land carbon sink weakening would become significant by 2°C.").

[5] 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.").

[6] 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 decades[2]—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."); *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.").

[7] *See* 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*, Masson-Delmotte V., *et al.* (eds.); *and* Intergovernmental Panel on Climate Change (2022) CLIMATE CHANGE 2022: IMPACTS, ADAPTATION, AND VULNERABILITY, *Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Pörtner H.-O., Roberts D. C., Tignor M., Poloczanska E. S., Mintenbeck K., Alegría A., Craig M., Langsdorf S., Löschke S., Möller V., Okem A., & Rama B. (eds.).

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

[9] The Arctic Council has two working groups and two expert groups that work on controlling methane emissions. These two working groups, the Arctic Contaminants Action Program (ACAP) and Arctic Monitoring & Assessment Programme (AMAP), each have an SLCP-specific expert group: the Expert Group on Short-Lived Climate Pollutants (within ACAP) and the Expert Group on Black Carbon and Methane (within AMAP). *See* Arctic Council, *Black Carbon and Methane Expert Group* (*last visited* 5 February 2023); Arctic Council, *Arctic Contaminants Action Program* (*last visited* 5 February 2023); *and* Arctic Council, *AMAP and the Arctic Council* (*last visited* 5 February 2023).

[10] Intergovernmental Panel on Climate Change (28 February 2022) *Climate change: a threat to human wellbeing and health of the planet. Taking action now can secure our future*, Newsroom ("Any further delay in concerted anticipatory global action on adaptation and mitigation will miss a brief and rapidly closing window of opportunity to secure a liveable and sustainable future for all, said [AR6 WGII co-chair] Hans-Otto Pörtner."). *See also* Intergovernmental Panel on Climate Change (2022) *Summary for Policymakers*, *in* CLIMATE CHANGE 2022: IMPACTS, ADAPTATION, AND VULNERABILITY, *Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Pörtner H.-O., Roberts D. C., Tignor M., Poloczanska E. S., Mintenbeck K., Alegría A., Craig M., Langsdorf S., Löschke S., Möller V., Okem A., & Rama B. (eds.), SPM-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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Mitigating climate disruption in time: A self-consistent approach for avoiding both near-term and long-term global warming

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The ongoing and projected impacts from human-induced climate change highlight the need for mitigation approaches to limit warming in both the near term (<2050) and the long term (>2050). We clarify the role of non-CO_2 greenhouse gases and aerosols in the context of near-term and long-term climate mitigation, as well as the net effect of decarbonization strategies targeting fossil fuel (FF) phaseout by 2050. Relying on Intergovernmental Panel on Climate Change radiative forcing, we show that the net historical (2019 to 1750) radiative forcing effect of CO_2 and non-CO_2 climate forcers emitted by FF sources plus the CO_2 emitted by land-use changes is comparable to the net from non-CO_2 climate forcers emitted by non-FF sources. 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 coemitted aerosols) and lead to temperatures exceeding 2 °C before 2050. In contrast, pairing decarbonization with additional mitigation measures targeting short-lived climate pollutants 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 and 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 time frame. Our analysis demonstrates the need for a comprehensive CO_2 and targeted non-CO_2 mitigation approach to address both the near-term and long-term impacts of climate disruption.

climate mitigation | short-lived climate pollutants | fossil fuel radiative forcing | near-term warming | non-CO_2 climate effects

Significance

This study clarifies the need for comprehensive CO_2 and non-CO_2 mitigation approaches to address both near-term and long-term warming. Non-CO_2 greenhouse gases (GHGs) are responsible for nearly half of all climate forcing from GHG. However, the importance of non-CO_2 pollutants, in particular short-lived climate pollutants, in climate mitigation has been underrepresented. When historical emissions are partitioned into fossil fuel (FF)- and non-FF-related sources, we find that nearly half of the positive forcing from FF and land-use change sources of CO_2 emissions has been masked by coemission of cooling aerosols. Pairing decarbonization with mitigation measures targeting non-CO_2 pollutants is essential for limiting not only the near-term (next 25 y) warming but also the 2100 warming below 2 °C.

Global warming is causing climate disruption today. At about 1.1 °C warming above preindustrial temperature (1), these impacts are being felt sooner and more intensely than previously projected (2). The frequency and intensity of climate and weather extremes have increased due to human-induced climate changes (1), and impacts such as displacements due to extremes are expected to grow with additional global warming (2).

We make a distinction between near-term warming and long-term warming: Near-term warming refers to the warming from now until 2050, while long-term refers to the period beyond 2050. This distinction omits the "mid-term (2041 to 2060)" recently introduced in the Intergovernmental Panel on Climate Change's (IPCC) Sixth Assessment Report (AR6) (1). When the focus is on long-term, decarbonization to reach net-zero carbon dioxide emissions should be the foremost goal. However, a new set of issues has emerged because of the link between warming and extreme weather (3) and the risk of crossing uncertain tipping points that increase with additional warming (1, 4).

Every region is experiencing extreme weather impacts from climate change (2, 5). The number of potentially fatal humid heat events doubled between 1979 and 2017 (6), while heat-related mortality in people over 65 y increased 53.7% (7). Such fatal humid heat events are expected to become common in the tropics at global average temperatures above 1.5 °C (8, 9). Increases in humid heat also reduce labor productivity, with current losses of annual gross domestic product up to 6% in tropical countries (7) and nonlinear increases under warming (10). Actions that limit 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*)" (2).

The critical need to curb near-term warming and limit warming to well below 2 °C requires broadening the zero carbon dioxide emissions approach, which focuses on mitigating the long-term warming, with other approaches that can quickly reduce the near-term warming by including non-CO_2 warming pollutants as an additional major

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focus of climate mitigation actions. The science of non-CO_2 warming pollutants dates back to 1975 with the discovery of the supergreenhouse effect of chlorofluorocarbons (CFCs) (11) followed by the addition of methane (CH_4) and nitrous oxide (N_2O) in 1976 (12). A comprehensive review of non-CO_2 warming agents by a United Nations–commissioned group in 1985 (13) concluded that non-CO_2 greenhouse gases (GHGs) were contributing as much as CO_2 to warming and projected that for the period between 1980 and 2030 non-CO_2 gases were likely to continue contributing as much as CO_2 to warming. These findings and projections have been confirmed by the most recent IPCC reports (14–17). We summarize these in the next section.

Independently, a series of studies that began in the 1970s concluded that fossil fuels (FFs), while contributing to global warming through CO_2 emissions, were also leading to global dimming and resulting cooling by increasing atmospheric aerosol particles (18, 19). While the overall aerosol effect is strongly negative due to emissions of sulfates, nitrates, and some organics that primarily reflect sunlight, there are other aerosols such as black carbon (BC) and brown carbon that absorb sunlight and thus contribute to global warming. The findings of the three decades of studies have been confirmed by the most recent IPCC report, which concludes that as of 2019 the net radiative forcing from cooling aerosols is around $-1.5\ Wm^{-2}$ (excluding about $+0.38$ from the aerosol-radiation forcing from BC and its effect on surface albedo). The CO_2 radiative forcing is $2.16\ Wm^{-2}$ and radiative forcing due to non-CO_2 GHGs and BC is $2.10\ Wm^{-2}$ (15).

Despite the general recognition of the role of non-CO_2 pollutants in climate mitigation, their contribution to warming as well as their potential for near-term cooling has been underappreciated in part due to inconsistencies between representation of climate forcing between IPCC Working Group I (WGI: Physical Scientific Basis), which includes all pollutants, and Working Group III (WGIII: Mitigation of Climate Change), which focuses on CO_2 and the subset of GHGs covered under the Kyoto Protocol, hence excluding halogenated gases covered by the Montreal Protocol and both warming and cooling aerosols that are primarily coemitted with CO_2 from FF usage. As we discuss in the next section, since FF combustion is the primary source of CO_2 emissions and also the source of some non-CO_2 pollutants, the extent to which decarbonization strategies to reduce FF emissions also reduce non-CO_2 emissions is ambiguous in many mitigation studies due to study design, leading some to question the benefits of early and fast targeted action in reducing non-CO_2 emissions (20).

The focus on CO_2 underpins the concept of carbon budget, which has been used to construct decarbonization pathways to meet specified long-term warming levels (21). While it has long been known that the coincidental cancelling of non-CO_2 warming and aerosol cooling was unlikely to persist due to differences in their sources and residence times (22), few carbon-budget-based studies have included the tight linkage between CO_2 mitigation and reduction in cooling aerosol emissions until recently (23).

Many publications and reports by scientific agencies (24–32) highlighted the role of non-CO_2 for rapid near-term climate mitigation, specifically short-lived climate pollutants (SLCPs)—methane (CH_4), BC, hydrofluorocarbons (HFCs), and tropospheric ozone (O_3)—but these have not captured the attention of global mitigation actions, which still focuses largely on CO_2 emissions.

There are two primary objectives of this study: first, clarifying the role of non-CO_2 GHGs (short-lived and long-lived) and aerosols (warming and cooling) in the context of the need for near-term and long-term climate mitigation, and second, clarifying the net effect of the FF phaseout in decarbonization, which involves both cooling due to cutting CO_2 emissions and warming due to unmasking of cooling aerosols coemitted by FF use. Unless otherwise stated, we rely on forcing values in the IPCC WGI reports published in 2021 and 2013.

Contributions to Radiative Forcing: CO_2 vs. Non-CO_2 GHGs (Excluding Aerosols)

Previous reports of IPCC WGI have consistently found that CO_2 and non-CO_2 GHG and GHG precursor emissions contribute close to equal shares (52 to 57% for CO_2 and 43 to 48% for non-CO_2 GHG) to climate forcing in radiative forcing terms when excluding aerosols (*SI Appendix*, Table S1). These results are reproduced in Fig. 1 *A* and *B*. In contrast, IPCC WGIII states in the Fifth Assessment Report (AR5) that "CO_2 emissions from fossil fuel combustion and industrial processes contributed about 78% of the total GHG emission increase from 1970 to 2010, with a similar percentage contribution for the period 2000–2010 … . Annually, since 1970, about 25% of anthropogenic GHG emissions have been in the form of non-CO_2 gases" (33). A similar statement was made by WGIII in the Fourth Assessment Report (AR4). However, these statements are inconsistent with WGI science and contribute to confusion for several reasons:

- First, GHG emissions considered by WGIII only include CO_2 (from FF use and forestry and other land use, [FOLU]), CH_4, N_2O, and HFCs and omit nonmethane tropospheric ozone precursors, CFCs, hydrochlorofluorocarbons (HCFCs), and other ozone-depleting substances covered by the Montreal Protocol (*SI Appendix*, Fig. S1). Taking into account these omitted non-CO_2 climate forcers using the EDGARv5.0 emissions database (34) for CO (as a proxy for nonmethane O_3 precursors) and National Oceanic and Atmospheric Administration and AGAGE (35) network data for CFC/HCFC/halon emissions, the average non-CO_2 GHGs and GHG precursors share over 1970 to 2010 is 39% (instead of the 25% quoted in WGIII reports) using the 100-y global warming potential (GWP_{100}) metric and 59% using GWP_{20}.
- Second, presenting the increase in emissions between two years (1970 and 2010) provides limited if not misleading insights into the actual forcing and climate impacts. We offer two examples, all of which adopt IPCC WGI estimates. 1) For the years 1993, 1998, 2005, 2011, and 2019, the percentage of CO_2 forcing (from all sources) compared with the total GHGs forcing ranges from 52 to 57% (*SI Appendix*, Table S1). The non-CO_2 GHGs contribute the balance of 43 to 48% (*SI Appendix*, Tables S1 and S2). 2) The contribution of the CO_2 forcing from just FFs to the total GHGs forcing is 38% for 2011 and 43% for 2019. The basic inference is that the WGIII finding of "CO_2 emissions from fossil fuel combustion and industrial processes contributed about 78% of the total GHG emission increase from 1970 to 2010" cannot be used to infer the contribution of CO_2 or FFs to either the radiative forcing or the resulting climate changes.

In short, the conclusion by WGIII that CO_2 from FF combustion contributed 78% of the total GHG emissions increase from 1970 to 2010 significantly underrepresents the nearly equal contribution of non-FFs as well as that of non-CO_2 GHGs to the total radiative forcing, which are described in the next two sections. Revisiting this historical accounting puts

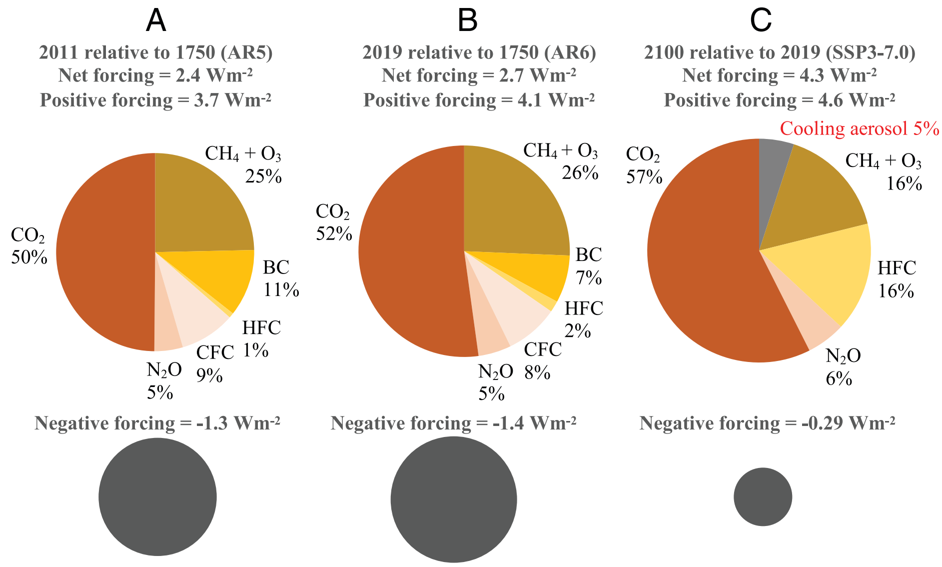

Fig. 1. Positive radiative forcing from long-lived GHGs (orange), short-lived GHGs, GHG precursors, and BC (aerosol–radiation interaction and snow albedo effects only) (yellow) and negative forcing from individual aerosol direct effects (aerosol–radiation interaction) and the total aerosol indirect effects (aerosol–cloud interaction) (separate gray pie) in (*A*) 2011 relative to 1750, from AR5 (14) and (*B*) 2019 relative to 1750, from AR6 (15). (*C*) The forcing at 2100 relative to 2019, under SSP3-7.0 emissions (49). Note the negative forcing due to assumed BC and CFC reduction and the positive forcing due to decline of cooling aerosols. Area of each pie chart is scaled to positive or negative forcing. See *SI Appendix*, Fig. S5 for bar chart version and *SI Appendix*, Table S6A for data.

into perspective the role of non-CO_2 emissions in the current global warming and serves as a reminder of the need to consider all sources of climate forcing when assessing mitigation strategies.

This comparison of WGI and WGIII approaches also further underscores the importance of separately accounting for short- and long-lived pollutant emissions, as discussed by Daniel et al. (36) and recently called for by Allen et al. (37). Reporting these pollutants separately allows for consideration not only of potential effects of mitigation measures by source and implications for coemissions but also an assessment of temperature impact on multiple time horizons of interest (1). With 1.5 °C expected to be crossed in the early 2030s (1, 38), Abernethy and Jackson (39) have advocated for choosing time horizons for GHG aggregation metrics consistent with temperature goals, specifically supporting the use of GWP_{20} over the GWP_{100}. A similar argument can be made in the context of the urgency to slow warming in the near term (2). In addition, common usage of aggregation metrics (e.g., GWP, GWP*, and global temperature potential) excludes very short-lived climate pollutants that are not well-mixed, such as aerosols and GHG precursors, but that can have significant implications for future warming (40, 41).

Contributions to Radiative Forcing: FFs vs. Non-FFs (Including Aerosols)

Here we clarify the historical contributions to present-day radiative forcing from FF and non-FF sources. Many heat-trapping gases and particles originate from both FF and non-FF sources, while others such as N_2O and halocarbons are primarily associated with non-FF sources. First, we calculate the relative share of emissions from FF and non-FF sources for GHGs alone, summing historical emissions pollutant by pollutant between 1850 and 2015 for each GHG based on source (42) and for future (after 2015) emissions using the FF coemission factors from Shindell and Smith (43) as described in *SI Appendix*. These shares are then applied to the total present-day radiative forcing in 2011 as in IPCC AR5 WGI (14) and 2019 as in IPCC AR6 WGI (15). Fig. 2 and *SI Appendix*, Table S2 show that for historical forcing (1750 to 2019) GHG from FF sources contributes about 53% of the total current GHG forcing, approximately the same as GHG forcing due to non-FF sources. However, if GHG emissions were to cease, residual forcing from long-lived GHG, predominantly FF CO_2, would dominate as shorter-lived pollutants would be rapidly removed.

Next, we consider warming and cooling aerosols. For forcing estimates related to aerosols, we distinguish effective radiative forcing (ERF) due to aerosol-radiation interaction (ERF_{ari}) for individual species from aerosol–cloud interaction (ERF_{aci}) considered separately as a lump-sum "indirect" forcing term associated with total aerosol emissions (*SI Appendix*). Previous studies have shown that the coemission of aerosols from FF combustion can result in warming or cooling with distinct temporal and spatial patterns (27, 44). Many studies have identified the importance of cooling aerosols—primarily sulfates (with SO_2 as the precursor), nitrates (NO, NO_2, and NH_3), and organic carbon—in masking GHG warming (1, 14). Fig. 1 shows the relative contributions of warming GHG, GHG precursors, and BC in comparison to the cooling from cooling aerosols relying on radiative forcing from historical emissions in recent IPCC reports, and how the relative contributions evolve in a reference scenario (SSP3-7.0) in 2100 relative to 2019.

The net forcings for all CO_2 and non-CO_2 FF (Fig. 2*A*) and non-FF non-CO_2 (Fig. 2*B*) sources are based on Hoesly et al. (42) for the period through 2015. For 2016 to 2019, we use the Shared Socioeconomic Pathways (SSP) scenario and adopt Shindell and Smith's (43) values for the coemission factors. We obtain similar results using radiative forcing values from AR6 WGI (*SI Appendix*, Table S3). For the radiative forcing from CO_2 emitted by FF as well as non-FF sources and non-CO_2 emitted by just FF, nearly half of the positive forcing (2.5 Wm^{-2}) in 2019 is masked by negative forcing of cooling aerosols (–1.1 Wm^{-2}), resulting in a net positive forcing of 1.4 Wm^{-2}. The forcing of cooling aerosols from non-FF non-CO_2 sources is only –0.2 Wm^{-2} compared to a positive forcing of 1.4 Wm^{-2}. Thus, the net forcing from non-FF non-CO_2 sources is 1.2 Wm^{-2} in 2019, or 45% of total net forcing when aerosols are included. The contribution to the net forcing from FFs (CO_2 and other

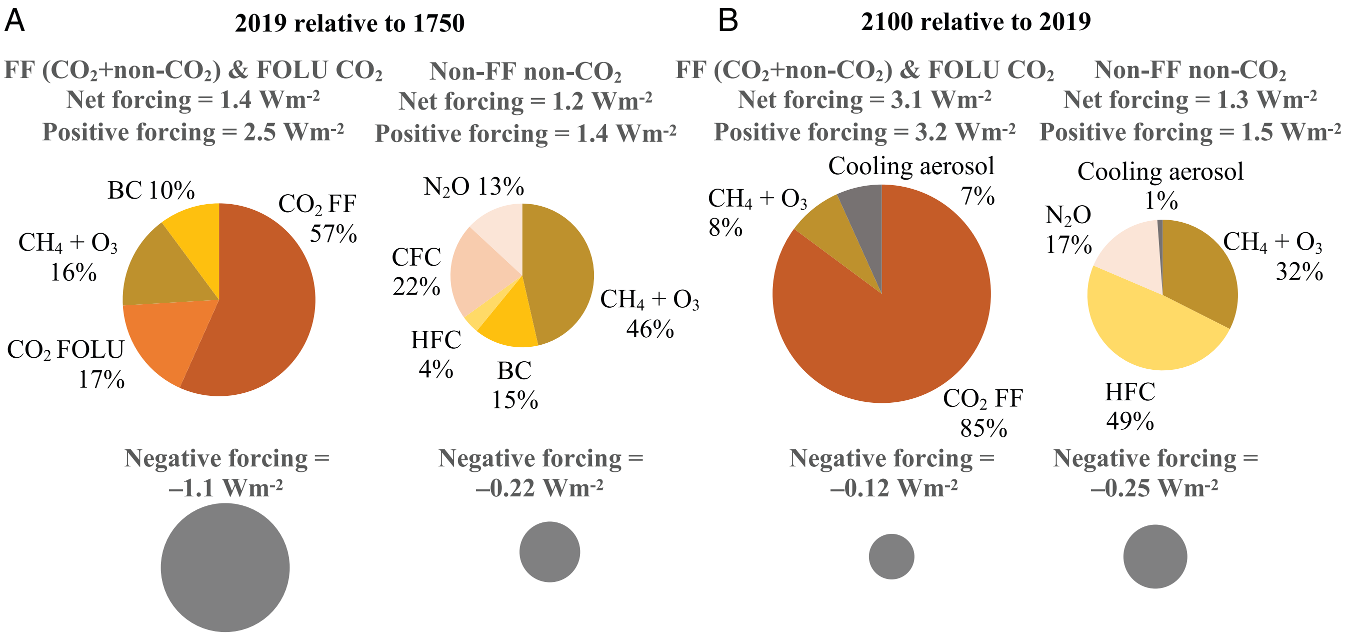

Fig. 2. (*A*) Contributions to 2019 radiative forcing from emissions by FF (CO_2+non-CO_2) sources and CO_2 from land-use changes (Forestry and Other Land Use, FOLU CO_2) compared with emissions from non-FF non-CO_2 sources based on ref. 42 and coemission factors from ref. 43 from this study, with similar results using radiative forcing values from AR6 WGI (*SI Appendix*, Table S3). (*B*) Contribution to the 2100 radiative forcing (relative to 2019) based on future emissions in SSP3-7.0 (49) partitioned by source using coemission factors from ref. 43. Area of each pie chart is scaled to positive or negative forcing. Data in *SI Appendix*, Table S6*B*.

GHGs) is 39% when aerosols are included and from non-FF sources is 61%.

The picture depicted above changes in the projection through 2100 under the limited climate policy SSP3-7.0 scenario. By 2100, around 70% of net forcing relative to 2019 is due to FF and other CO_2 emissions, emphasizing the importance of adopting decarbonization together with strategies targeting non-CO_2 to address near-term and long-term warming.

Contributions to Warming: CO_2 vs. Non-CO_2 and FFs vs. Non-FFs

The tendency to group CO_2 and non-CO_2 together irrespective of emission sources has contributed to a frequent misperception that CO_2, which comes predominantly from FF burning, is the only important contributor to observed warming. This misperception is understandable: Our model shows that out of the 1.01 °C warming simulated for 2015, CO_2 has contributed 0.98 °C (*SI Appendix*, Table S4). Thus, one can indeed claim that to the first order the observed global warming of ∼1 °C is primarily due to CO_2. However, a closer look reveals that the magnitude of warming by non-CO_2 GHGs coincidentally cancels the cooling by all (FF & non-FF sources) aerosols (45–47) (*SI Appendix*, Fig. S2). Indeed, our model shows that the combined cooling effects of aerosols including the indirect effects via enhancing cloud albedo (–1.15 °C) has masked an amount of warming that is almost equal to the total non-CO_2 warming of 1.17 °C. This leads to a facile but false assumption that most non-CO_2 forcings have canceled one another and will continue to do so in the future and obscures the significance of the residence time of the pollutants for both short- and long-term climate mitigation.

Uncovering the flaw in this reasoning requires correctly attributing the masking from cooling aerosols. Ignoring sources and aerosols, CO_2 would appear to contribute about 55% of GHG warming (*SI Appendix*, Table S4). Considering only FF sources, *SI Appendix*, Table S4 shows that the warming from FF emissions (GHGs and BC) of 1.07 °C in 2015 is mostly masked by cooling of 0.88 °C from cooling aerosols that are coemitted with FF emissions. In contrast, while the warming from non-FF emissions (GHGs and BC) is equivalent in magnitude at 1.08 °C, only 0.26 °C is masked by coemitted cooling aerosols. This analysis reveals that about 80% of warming realized in 2015 is attributable to non-FF sources due to masking by cooling aerosols coemitted from FF sources. As these aerosols fall out of the atmosphere, the future net warming contribution from FF sources under SSP3-7.0 begins to dominate by the 2060s due to the longer residence time of CO_2.

Accurately attributing past warming is key to mitigation actions going forward. As decarbonization measures reduce FF use they also reduce the coemitted cooling aerosols (primarily sulfates) and unmask the warming from accumulated GHGs in the atmosphere. In the following section we describe the implications of such unmasking for near- and long-term mitigation potential of decarbonization and clarify the essential role of strategies targeting non-CO_2 pollutants in limiting warming through 2050.

Mitigation Strategies in Time: Decarbonization and Targeted Mitigation

Reducing CO_2 emissions by shifting from FF to low-carbon energy sources is underway and needs to accelerate to achieve net-zero CO_2 emissions by midcentury or sooner consistent with the Paris temperature target (48). While getting to net-zero CO_2 emissions is critical and essential for stabilizing long-term warming, it also reduces coemitted cooling aerosols and causes weak near-term warming, which can be offset by reductions in non-FF pollutants (43). Few studies, however, have specifically quantified the contribution of measures targeting non-CO_2 independent from FF usage, such as the 16 measures in the 2011 UNEP/WMO Assessment (31).

Our analysis disentangles CO_2, SLCPs, and cooling aerosols by asking the following question: Under an aggressive climate mitigation scenario (such as the marker version of SSP1-1.9), what is the avoided warming due to decarbonization alone (i.e., reduction in FF usage) and when paired with non-decarbonization-related mitigation targeting non-CO_2 pollutants? We answer this question by explicitly accounting for the associated reductions in coemitted pollutants including cooling aerosols from each mitigation approach. As described in *SI Appendix*, we use SSP scenarios (49) and apply coemissions factors to partition emissions of individual pollutants into FF-related and non-FF-related (43). We consider three cases (Table 1): As a reference case we adopt the limited climate policy high-emission scenario SSP3-7.0, a middle case with only decarbonization-driven emissions reductions, and a "decarb+targeted" case including mitigation measures that go beyond decarbonization to target SLCPs and other non-CO_2 pollutants (based on SSP1-1.9). We construct the "decarb-only" case by partitioning the reduction in emissions in the "decarb+targeted" case relative to the baseline case into decarbonization-driven and other targeted measures. Our approach differs from ref. 43 in that we use the SSP3-7.0 scenario to quantify the nondecarbonization mitigation potential from methane and BC. This includes mitigation measures targeting the ~10% of methane emissions from abandoned coal mines and wells due to fugitive emissions that are not directly affected by decarbonization-driven reductions in FF use (*SI Appendix*).

All emission pathways including total and individual forcing were converted to temperature trajectories using the energy balance climate model RXM (*SI Appendix*), which has been validated in our earlier studies with climate models used in IPCC assessments (27, 30, 50, 51) and observed warming trends for the 20th century (*SI Appendix*, Fig. S3). Both the equilibrium and the transient climate sensitivity of the RXM model used in our study is within a few percent of the central values recommended in AR6. Our results for the avoided warming in the "decarb+targeted" case (*SI Appendix*, Table S5) are consistent with the results for methane, ozone precursor, and HFC abatement reported in AR6 WGI (52), which also used SSP3-7.0 as a reference case and SSP1-1.9 as the mitigation case, but do not account for source partitioning. With RXM we find avoided warming of 0.3 °C by 2040 from SLCP mitigation compared to 0.1 to 0.4 °C in AR6. The impact of SLCP reductions in 2100 is 0.5 to 1.3 °C in AR6, compared to 1.7 °C in our scenarios, which likely reflects the more stringent HFC and N_2O reductions in our adapted mitigation scenario. Our methane mitigation benefit of ~0.2 °C by 2050 is smaller than the ~0.3 °C in a recent assessment based on similar abatement (38), suggesting that the sensitivity of RXM to methane is lower than that in the three-dimensions composition-climate models (but well within uncertainties) (*SI Appendix*).

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 coemitted cooling aerosols (Fig. 3*A*). 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 (*SI Appendix*, 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 and Fig. 3*B*), 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 four times larger than the net benefit of decarbonization alone (0.07 °C) (*SI Appendix*, Table S5). These results are calculated using an average BC forcing at present of 0.33 Wm^{-2} relative to preindustrial (direct and snow albedo; *SI Appendix*), which is consistent with the AR6 range (0.30 ± 0.2 Wm^{-2} for ERF_{ari} and 0.38 Wm^{-2} including snow albedo effects) (56). Combining all targeted non-CO_2 measures results in a net avoided warming in 2060 of 0.43 °C. Pairing decarbonization measures with targeted measures can achieve 0.25 °C in total avoided warming, a level that is likely to be detected (57) over a decade earlier (~2047) than

Table 1. Simulated warming rates and other key metrics under reference, decarbonization only, and decarb+ targeted scenarios

Scenario	Warming rate, °C/decade (2020–2040)	Year when warming rate drops below 0.25 °C/decade	Year of peak warming rate	Year when crossing 1.5 °C warming	Year when crossing 2 °C warming	Warming in 2030 relative to 1850–1900, °C	Warming in 2050 relative to 1850–1900, °C
Reference: Limited climate policy, high emission (SSP3-7.0)	0.36 (0.34–0.38)	—	—	2031–2033	2045–2046	1.5 (1.4–1.5)	2.2
Decarbonization-driven: Scenario using decreasing FF primary energy as in SSP1-1.9 and associated emission factors to calculate decline in FF-related emissions compared to reference	0.37 (0.35–0.39)	2049–2052	2030	2030–2032	2045–2046	1.5 (1.4–1.5)	2.1
Decarbonization and Targeted measures: Aggressive climate policy, low emission (based on SSP1-1.9)	0.31 (0.29–0.32)	2035–2037	2023	2030–2033	—*	1.5 (1.4–1.5)	1.85 (1.8–1.9)

The range of years reflects the uncertainty in present-day forcings of BC and cooling aerosols.
*Peak temperature of 1.9 °C in 2060s before declining to 1.7 °C in 2100.

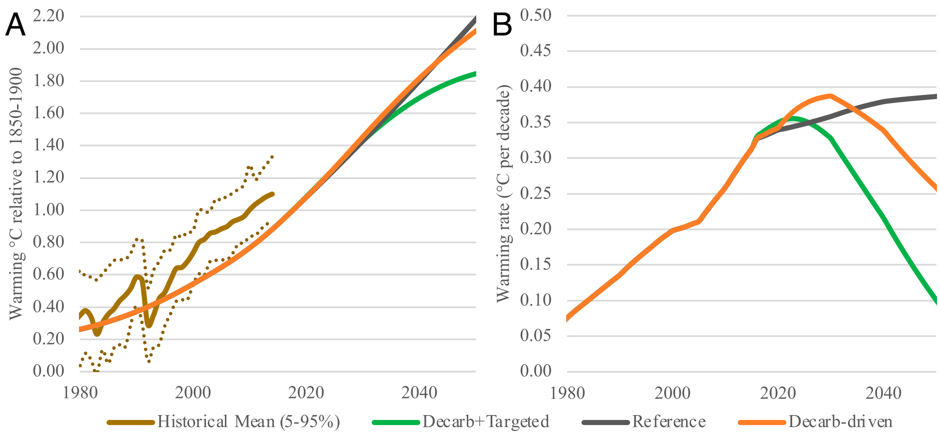

Fig. 3. (*A*) Historical and future temperature projections through 2050 calculated using the RXM energy balance model based on emissions scenarios from the SSP database (49) for reference scenario (SSP3-7.0), decarbonization-driven mitigation scenario (this study), and an "decarb+targeted" scenario including aggressive decarbonization and targeted SLCP mitigation (adapted from SSP1-1.9). Historical curve (past simulated warming) is from figure SPM8.a (47, 64). (*B*) Rate of warming (degrees Celsius per decade) in the reference SSP3, decarbonization only, and "decarb+targeted" mitigation cases.

decarbonization alone (2060; *SI Appendix*, Table S5). The avoided warming due to decarbonization begins to exceed that due to the targeted measures only after 2080 (*SI Appendix*, Fig. S4).

Only about 30% of the avoided warming from CH_4 over the period 2020 to 2040 is related to decarbonization measures (*SI Appendix*, Table S5). The larger portion of CH_4 reduction due to targeted measures may be due to a slower rate of reduction in natural gas usage in the marker SSP1-1.9 scenario (60% down in 2050 relative to 2015) compared with decrease in coal combustion (more than 90% down). Consistently, about two-thirds of non-CH_4-induced ozone mitigation is also due to non-CO_2 targeted measures rather than a direct consequence of decarbonization. These results are also consistent with UNEP/WMO (31), which found that measures to reduce methane and BC emissions cut warming in 2030 by half compared with a reference case and that aggressive CO_2 reductions, in themselves, did little to mitigate warming in the first 20 to 30 y, in part due to unmasking of coemitted cooling aerosol.

Fig. 3*A* shows that combining targeted mitigation strategies with decarbonization keeps warming below 2.0 °C, while decarbonization alone breaches 2.0 °C in 2045 in our scenario. Moreover, decarbonization alone increases the warming rate in the near term (Table 1). Notably, the warming rate in the decarbonization scenario would not drop below the current rate of warming until the 2040s (Fig. 3*B*). Pairing decarbonization with measures targeting SLCP slows the rate of warming a decade or two earlier than decarbonization alone.

Consideration of Uncertainties

The largest uncertainties in our analysis relate to the mitigation pathways chosen, both the reference limited climate policy scenario and the low-emission mitigation scenarios. While current CO_2 emissions commitments track closer to SSP2-4.5, the key insight of our study is not about additionality in terms of new policy measures. Rather, our study seeks to distinguish between mitigation policy focused on FF decarbonization alone versus decarbonization plus targeted measures. For this reason, we selected as a reference the high-emission scenario SSP3-7.0 and as a low-emission scenario SSP1-1.9, which are the same end-member scenarios as assessed in AR6 WGI (52).

The second major source of uncertainty is the nearly threefold uncertainty in climate sensitivity. All of the projected warming numbers presented here should be interpreted as median value with 50% probability. A third source of uncertainty relates to our use of constant FF coemission factors in constructing the decarbonization-driven scenario. Since this partitioning approach is most valid in the near term, we focus our analysis on the period through 2050. A fourth source of uncertainty relates to our limited understanding of the role of aerosols in climate forcing and feedbacks in future projections due to the following aspects: 1) the assumption of mixing of various aerosol species, especially the potential enhancement of BC forcing when accounting for the mixing with other reflective aerosols (58), 2) the future changes of background cloud field due to the slow feedback process to GHG warming (59, 60), and 3) the future changes of background aerosols from natural sources such as dust and sea salt due to climatic changes affecting the emission processes related to soil condition and wind stress over ocean surface and related cloud impacts (e.g., ref. 61).

Conclusions

This study clarifies as well as establishes the need for a comprehensive and inclusive CO_2 and non-CO_2 mitigation approach with distinct decarbonization and SLCP targets to address both the near-term and long-term impacts of climate disruption. A review of IPCC reports leads to the inference that non-CO_2 GHGs are responsible for nearly half of all current climate forcing from GHGs. When accounting for aerosols and coemissions by source, the inference from our analyses is that about 80% of the realized warming as of 2015 is attributable to non-FF sources due to FF GHG emissions being masked by coemission of short-lived cooling aerosols. However, the importance of non-CO_2 pollutants, in particular SLCPs, and their role in climate mitigation has been underappreciated due to misperception arising from inconsistencies between IPCC WGI and WGIII reports. The tendency to attribute impact to pollutants rather than sources and to group all non-CO_2 together regardless of emissions sources has further entrenched this misperception due to coincidental cancelling of warming and cooling pollutants and the false impression that they will continue to cancel out in the future. When historical emissions are partitioned into FF- and non-FF-related sources, we find that nearly half of the forcing from FF and other CO_2 emissions has been masked by coemission of cooling aerosols. As a result, close to half of net radiative forcing, as of now, is attributable to non-FF sources of methane, F-gases, BC, and N_2O. However, this is likely to change in the future as decarbonization policies reduce FF emissions of both warming GHGs and cooling aerosol.

By 2100, absent climate policy, FF will be the largest source (about 70%, mostly due to CO_2) for global warming and resulting impacts on planet and society. Even in the shorter term, FF emissions are the largest source of air pollution particles and ozone, which contribute to premature mortality of over 8 million people per year (45, 62). Tropospheric ozone also leads to crop losses of 100 million tons or more (63). As we have repeatedly emphasized in this study, achieving net-zero carbon dioxide emissions by 2050 is essential to limit global warming below 2 °C beyond 2050.

Pairing decarbonization with targeted SLCP mitigation measures is essential to simultaneously limit both near-term warming and long-term warming below 2 °C and thus reduce risks from crossing tipping points. Importantly, these two strategies are complementary and not interchangeable. Absent deep cuts in non-CO_2 emissions, CO_2 abatement alone is unable to keep warming below even the 2 °C threshold by 2050. Decarbonization measures alone achieve about a third of potential avoided warming from methane mitigation by 2050, less than half of SLCP mitigation potential, and none of the reductions from measures targeting N_2O. Nor can cutting methane emissions this decade replace the need for net-zero carbon dioxide by 2050 to stabilize the climate this century. Similarly, deeper CO_2 reductions this decade do not replace the need for methane and other SLCP reductions to slow warming in the near term. Aggregation metrics such as GWP and GWP* are designed in terms of warming impacts over multiple decades and are seldom used in ways that account for the important differences between strategies that can reduce warming in the near term.

Adopting a comprehensive mitigation approach that pairs rapid decarbonization with "strong, rapid and sustained reductions in CH_4 emissions" (1) as recommended in the Global Methane Assessment (32) and additional targeted SLCP mitigation responds to the call from WGII for urgent action to slow warming in the near term (2). For example, over 100 countries joined the Global Methane Pledge in November 2021, committing to a collective goal of reducing global anthropogenic methane emissions by at least 30% below 2020 levels by 2030. If achieved, this target, which is consistent with the reduction in the "decarb+targeted" scenario analyzed here, would avoid 0.2 °C by 2050 (*SI Appendix*, Table S5).

Data Availability. All study data are included in the article and/or *SI Appendix*.

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Supplementary Information for

Mitigating Climate Disruption in Time: a self-consistent approach for avoiding both near-term and long-term global warming

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Materials and Methods

This paper conducts a quantitative modelling exercise for a combination of more than a dozen individual species including CO_2, N_2O, ozone-depleting substances such as CFCs and HCFCs, various cooling aerosols such as sulfate, NO_x, organic carbon, and the well-known group of SLCPs including black carbon, ozone, methane, and HFCs. The modelling exercise produces the relative contribution of those species to historical (1850–2015) and future (2016–2100) warming.

The IPCC AR6 WGIII report was published the same week as we received galley proofs for our paper, so we are not commenting further beyond noting that an initial review did not change our findings.

Historical decomposition into fossil-fuel related and non-fossil fuel related emissions are based on Hoesly et al. (1). For sulfate and other aerosols, some sectors in the SSP dataset are classified as fossil-fuel related, including aircraft, energy, industrial, shipping, residential/commercial, solvents production and transport, with the other sectors classified as non-fossil related (including agriculture waste burning, agriculture, forest burning, grassland burning, peat burning and waste). Emissions are partitioned into FF and non-FF based on the classification in Hoesly et al. (1). Aerosol emissions are then scaled to radiative forcing based on the present-day forcing values. Radiative forcing of GHGs (CO_2, N_2O and CH_4) are calculated from the corresponding concentrations due to FF and non-FF emissions. Note that the present day forcing is calibrated to reflect our latest understanding of the uncertainty, especially with regard to indirect aerosol-cloud effects of cooling aerosols (ERF_{aci} of $-0.7\ Wm^{-2}$ at present), and "all source" carbonaceous aerosols such as black carbon (+0.6 Wm^{-2} at present for “all sources” versus zero BC, with uncertainty range of 0.25 to 1.0 Wm^{-2}), and co-emitted partially absorbing organic aerosols (–0.5 Wm^{-2} at present-day). The SO_4 (with SO_2 as the precursor) forcing is taken as –0.6 Wm^{-2} at present and NO_x as –0.2 Wm^{-2}.

For the future period analysis, we consider three cases: a weak climate policy baseline case, a middle case with only decarbonization-driven emissions reductions, and an “decarb+targeted” case including policies beyond decarbonization targeting methane, HFCs, and other pollutants. The baseline and “decarb+targeted” scenarios and outputs are selected from the database of Shared Socioeconomic Pathways (SSP)(2). The AIM marker scenario SSP3-7.0, which has only weak climate policy, is selected as the baseline scenario (3). The IMAGE marker scenario SSP1-1.9, which is consistent with the 1.5°C pathway and is the ‘cleanest’ scenario among the published marker SSP scenarios, is selected as the aggressive climate change mitigation scenario (4, 5). Harmonized outputs for all scenarios are used (6). We use the IMAGE marker SSP1-1.9 scenario as the aggressive climate mitigation scenario for all species, except HFC and N_2O (see below).

We construct the middle “decarbonization” case by partitioning the decrease in emissions in the mitigation case relative to the baseline case into “decarb-driven” and other targeted measures. Most radiatively important species have both fossil fuel and non-fossil fuel related sources Shindell and Smith (7) Extended Data Figure S1 is used as *the present-day* share of current emissions that are FF-related for those species: methane (30%), black carbon (70%), sulfate

(96%), NO_x (96%), and organic carbon (40%). Since this partitioning approach is most valid in the near term, we focus our analysis on the period through 2050.

For future emissions, the FF-related portion of emissions sources is calculated using a scaling factor (akin to emission intensity: a ratio of mass over energy use) to estimate "decarb-driven" emission trajectories based on the decrease in fossil fuel primary energy usage in the mitigation scenario. Under the SSP1-1.9 scenario fossil fuel usage declines rapidly. As a result, FF-related emissions of those species would also decline. Thus, a middle of road pathway ("decarb-driven") is constructed by estimating the reduction in FF-related emission of each species due to decreased use of FF. The residual share is due to non-fossil fuel sources, such as agriculture, waste or use of solid biomass. It is assumed that there is no change in the future in non-FF-related share of the total emissions for the purpose of deriving the "decarb-driven" emissions cut. The CO_2 emissions reduction in this pathway is also associated with carbon capture and sequestration measures.

With the decarb-driven and "decarb+targeted" emission pathway (mostly based on SSP1-1.9), we then convert emissions into atmospheric concentrations for GHG species (CO_2, CH_4, N_2O), and then convert atmospheric concentrations into radiative forcing. Aerosol forcings are scaled based on emission trajectory for the future periods. Tropospheric ozone is not directly emitted, but is produced through chemical reactions involving methane, non-methane volatile organic compounds, and nitrogen oxides. The radiative forcing and warming from tropospheric ozone production are included in the radiative forcing calculated for methane and with the rest scaled with carbon monoxide emission.

Finally, the total and single forcing trajectories, including both historical and future periods, were converted to temperature evolution using an energy balance model RXM (8). The climate equilibrium sensitivity of RXM is taken as 3.05ºC for a doubling of CO_2, very close to the central value of 3ºC (with a *likely* range of 2.5-4ºC) recommended by AR5 and AR6 WGI. The transient climate response in RXM is shown to be 1.8ºC (8), identical to the central value of 1.8ºC (with a *likely* range of 1.4-2.2ºC). RXM has been well tested via comparison with observations, global climate models and models with intermediate complexity (9, 10); see also Figure S3. As shown in Supplementary Figure 21 of ref. (10), RXM yields a higher global mean temperature under SSP1-2.6 toward the end of the 21st century, compared to MAGICC.

Next, we detail the assumption of individual species in order to derive the decarb-driven scenarios.

Methane (CH_4) and tropospheric ozone (O_3). As noted above, tropospheric ozone is not directly emitted, but produced by chemical reactions involving methane, and hence is included as part of the methane emission contribution to warming. Note that the approach used here is simplified in its accounting for the ozone chemical response to methane, the climate response, and the carbon cycle response, leading to differences relative to global composition-climate models, and this may account for a smaller effect than that seen in those more detailed models (11).

The methane emission trend due to decarbonization is constructed by scaling the present-day portion of FF-related emission based on the future reduction of primary energy production. The same emission factor is used for coal and oil/gas because the 1:2 ratio of those present-day energy uses are similar to the Global Methane Budget 2000–2017 finding coal mining contributed 42 Tg CH_4 yr^{-1} and oil and gas contributed 80 Tg CH_4 yr^{-1} (12). Unlike most other fossil fuel emissions, methane comes largely from direct (fugitive) emissions during extraction (on the order of 3.7% of gross gas extracted in the Permian (13)), storage and distribution. Recent satellite observations found that 8 to 12% of global oil and gas methane emissions come from over 1,800 ultra-emitting sources and represent fugitive emissions not included in most current inventories (14). This underestimation from oil and gas would translate to about 2% difference in our approach for partitioning between fossil fuel and non-fossil fuel methane sources since oil and gas methane emissions make up about 22% of total anthropogenic methane emissions (12). Methane is also emitted from abandoned oil and gas wells (15), and often underestimated (16). Current estimates are ~10% of coal-related methane emissions are from abandoned mines (17). Furthermore, halting the use of FF will not reduce methane emissions from abandoned mines or wells. As a result, the actual decarbonization-related reductions are lower than if scaling directly to reduction in FF usage. Thus, in this study, the FF-related methane reduction is scaled down by 0.9 to account for the fact that unlike most other emissions, FF-related methane doesn't come from combustion only but also from extraction, storage, and distribution processes.

Other sources of anthropogenic methane emissions not directly related to fossil fuel include agriculture, animal, and municipal waste (56% of the total anthropogenic emissions) and biomass and biofuel burning (8%)(12). The non-decarbonization related methane reductions are calculated as the difference between the constructed decarb-related methane reduction and SSP1-1.9.

CFC, HCFC, halon, and HFC. Instead of relying on the SSP database, CFC, HCFC, and HFC forcing are adopted from (18). HFCs are manufactured gases primarily produced for use in refrigeration, air-conditioning, insulating foams, and medical and technical aerosol propellants. HFCs are not co-emitted with fossil fuel combustion. Emissions of HFCs are growing rapidly as HFCs are used to replace ozone depleting chlorofluorocarbons (CFCs), which were previously phased out under the Montreal Protocol, and hydrochlorofluorocarbons (HCFCs), which are now being phased out. HFC emissions in 2016, not including HFC-23, accounted for 0.025 Wm^{-2} of forcing and were projected to increase ten-fold to 0.25 Wm^{-2} by 2050 in the absence of controls agreed under the 2016 Kigali Amendment (19). For the reference scenario, we consider both high and low references as in (18). For the mitigation scenario, we considered KA mitigation, which yields 0.19ºC avoided warming in 2100. A more aggressive scenario with production phaseout in 2020 yields 0.38ºC avoided warming in 2100.

Nitrous oxide (N_2O). Instead of relying on the SSP database, N_2O forcings are adopted from scenarios in (19). In particular, zero anthropogenetic emission after 2020 is adopted as an aggressive illustration of mitigation potential in the future.

For forcing estimates related to aerosol species, we distinguish effective radiative forcing (ERF) due to aerosol-radiation interaction (ERF_{ari}) that is detailed below for individual species and aerosol-cloud interaction (ERF_{aci}) that is not well constrained and thus difficult to disaggregate among species. Thus, we consider ERF_{aci} separately as a lump-sum "indirect" forcing term associated with the total aerosol emissions, which has an average value of –0.50 Wm^{-2} for 2011 relative to 1850 (uncertainty range of –0.39 to –0.61). We also acknowledge that the ERF_{aci} estimates are subject to the background cloud spatial distribution which could change in future due to feedback process in response to overall global warming. This would impose additional uncertainty to the forcing estimates of future aerosols in this simple climate model framework.

Sulfate/sulfur dioxide (SO_2). The decarb-driven emissions trend for SO_2 is generated by scaling 96% of present-day emissions according to the corresponding future change in primary energy production from coal. Such an approach of scaling to coal use only, rather than the total fossil fuel energy use, is supported by the IPCC Emission Factor Database (https://www.ipcc-nggip.iges.or.jp/EFDB/find_ef.php), in which SO_2 emissions factor for coal are 10-100 times greater than for gasoline and oil. Natural gas combustion only emits a minimal amount of sulfur. The remaining portion of SO_2 emissions reduction (i.e., the difference between constructed pathway and SSP1-1.9), is due to any change in non-fossil fuel related emissions as well as the remainder of the FF-related emissions, which is presumed to be due to other dedicated mitigation measures, such as scrubbing.

Black carbon (BC). 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 (20, 21). Taking the ERF_{ari} only and snow albedo effect, BC contributes to an estimated +0.25

Wm^{-2} (22) to +0.9 to 1.1 Wm^{-2} at present (20, 23, 24). In this study, we adopt an average of 0.6 Wm^{-2} based on high and low forcing estimates for "all-source" forcing (0.25 to 1 Wm^{-2}). This gives an average present-day forcing of 0.33 Wm^{-2} for 2011 relative to 1850 (0.13 to 0.53), consistent with AR6 range (0.30±0.2 Wm^{-2} for ERF_{ari} and 0.38 Wm^{-2} including snow albedo effects)(25).

We address entanglement of BC emissions with GHG and other aerosol emissions in two ways: first, we adopt a 70% co-emission factor for BC for FF sources based on (7), such that part of BC mitigation is achieved through decarbonization, while the non-FF related BC, such as from biofuel burning, is included in targeted measures. Second, we include in our discussion of uncertainty that we have not explicitly accounted for the potential enhancement of positive forcing of BC when accounting for the mixing with other reflective aerosol (26). We also note that a portion of the lump-sum ERF_{aci} negative forcing might be attributable to BC, which would lower the total BC forcing (27). Thus, BC forcing has substantial uncertainties in both directions, motivating our use of high and low forcing estimates.

Annual estimations between 4.5 Tg (28) to 7.2 Tg (29) of global black carbon were emitted in 2010 from anthropogenic sources, with forest and savannah fires (not including agricultural waste burning) contributing about 2.3 Tg per year (29). The primary sources of anthropogenic black carbon are combustion of diesel and solid fuels for heating and cooking in households (57%), road and non-road transport (24%), and industry (6%). Other categories include agriculture open field burning (5%), oil and gas flaring (3%), large scale industrial combustion (2%), international shipping and aviation (2%), and waste (1%)(29).

Other cooling aerosols (OC and NO_x). Corresponding portions of other species (OC, NO_x) emissions trends are scaled based on primary energy due to total fossil fuel (coal+gas+oil) using the shares derived from (7). We do not differentiate between fossil fuel sources for OC based on inventories suggesting similar order of magnitude emissions (29).

Land cover and solar activity. Limited forcing due to land cover change and solar activities in the past is factored in, but their potential change in the future is not considered.

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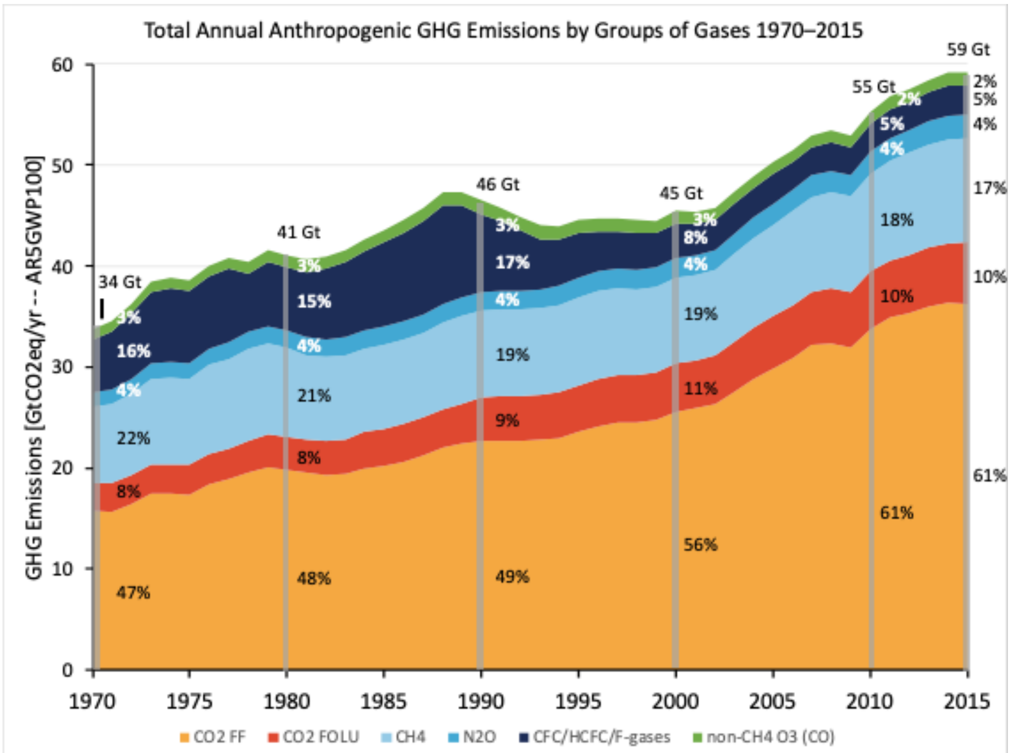

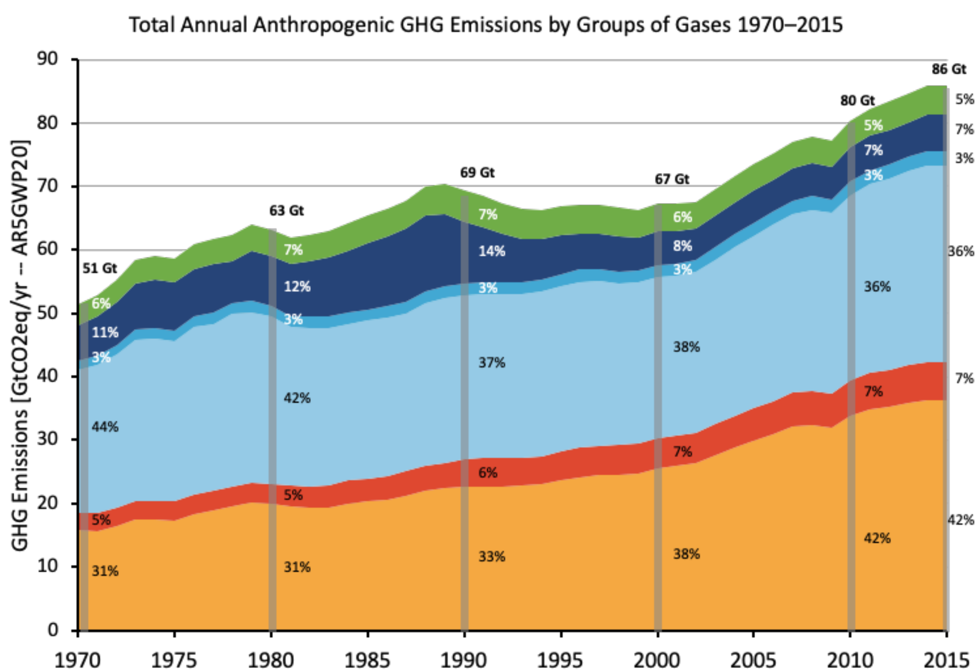

Figure S1. Total GHG emission in $CO_{2\text{-eq}}$. This is revised from IPCC AR5 WGIII figure SPM.1 by taking into account omitted GHGs such as non-CH_4 related tropospheric O_3 (using CO as a proxy for precursors and using GWP_{100} of 2.2 scaled by 0.94 based on Table 8.A.4 in Myhre *et* *al.* (30)) from EDGARv5.0 (31), and CFC, HCFC, and halons from NOAA and AGAGE networks. a) using GWP_{100}; b) using GWP_{20} from AR5 (30).

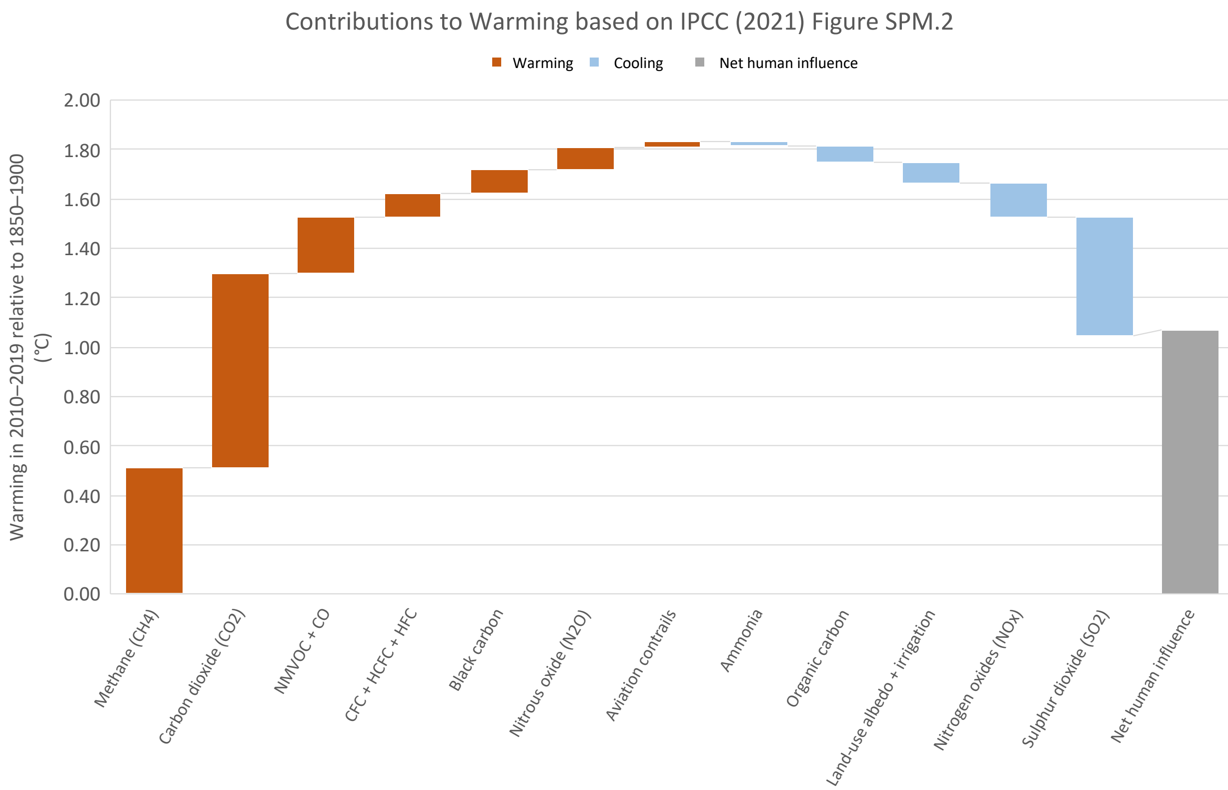

Figure S2. Contributions to observed warming in 2010–2019 relative to 1850–1900 adapted from Figure SPM.2 (32, 33).

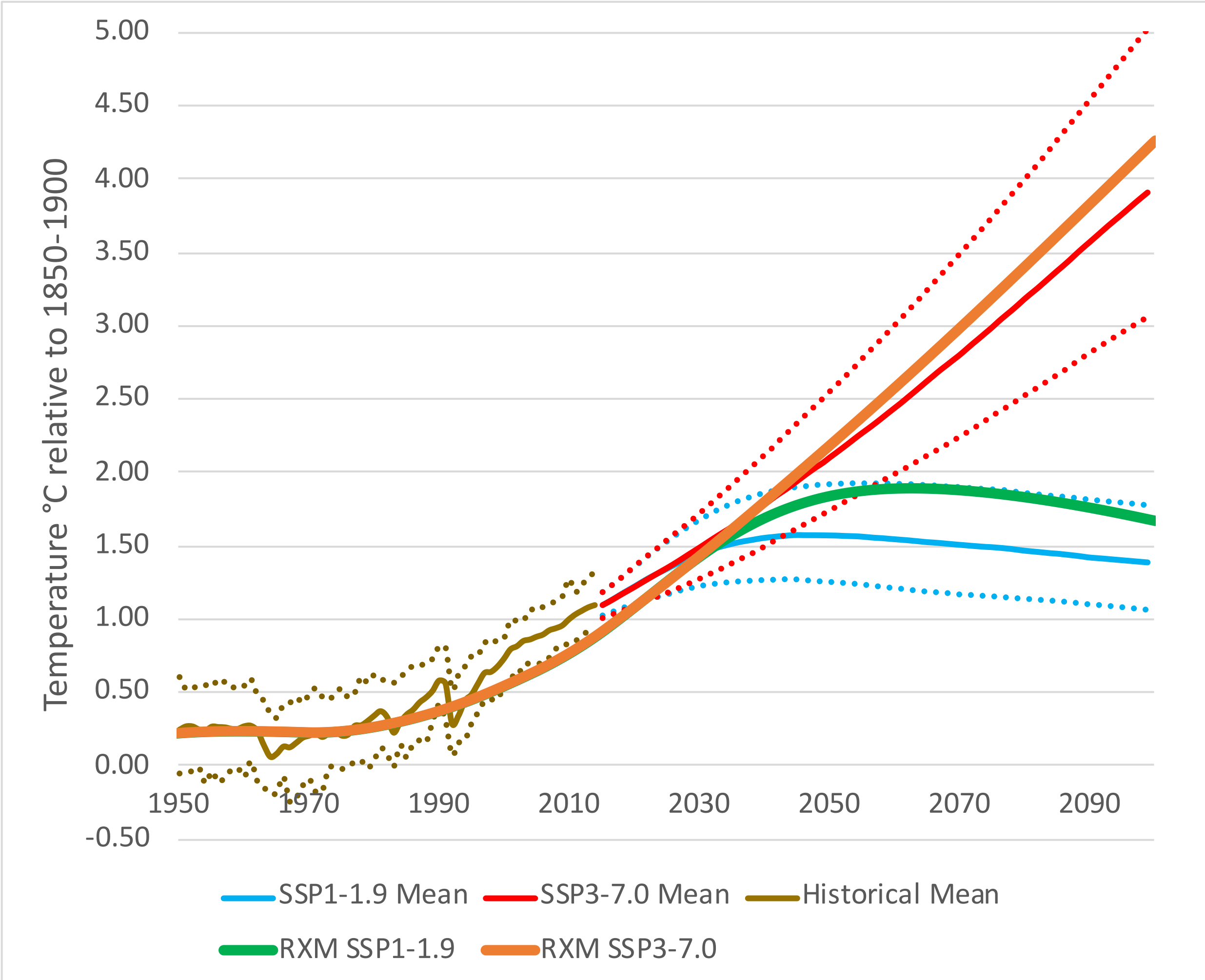

Figure S3. Comparison of RXM model temperature output for SSP1-1.9 (green) and SSP3-7.0 (orange) compared with AR6 WGI Figure SPM8.a for historical (brown), SSP1-1.9 (blue), and SSP3-7.0 (red), wish dashed lines showing 5-95% range (32, 34). RXM reproduces warming and trends for 1950-1990, and gives a slower rate of warming in recent decades (1990-2015) than observed, and higher rate of warming than SSP simulations for 2015-2030. This likely reflects model sensitivity to aerosol forcing. Aerosol forcing increased for 1950-1900 and is projected under SSP1 to decrease for 2015-2030. Figure SPM8.a SSP curves are adjusted by +0.85°C to match observed warming increase between 1850-1990 and 1995-2014.

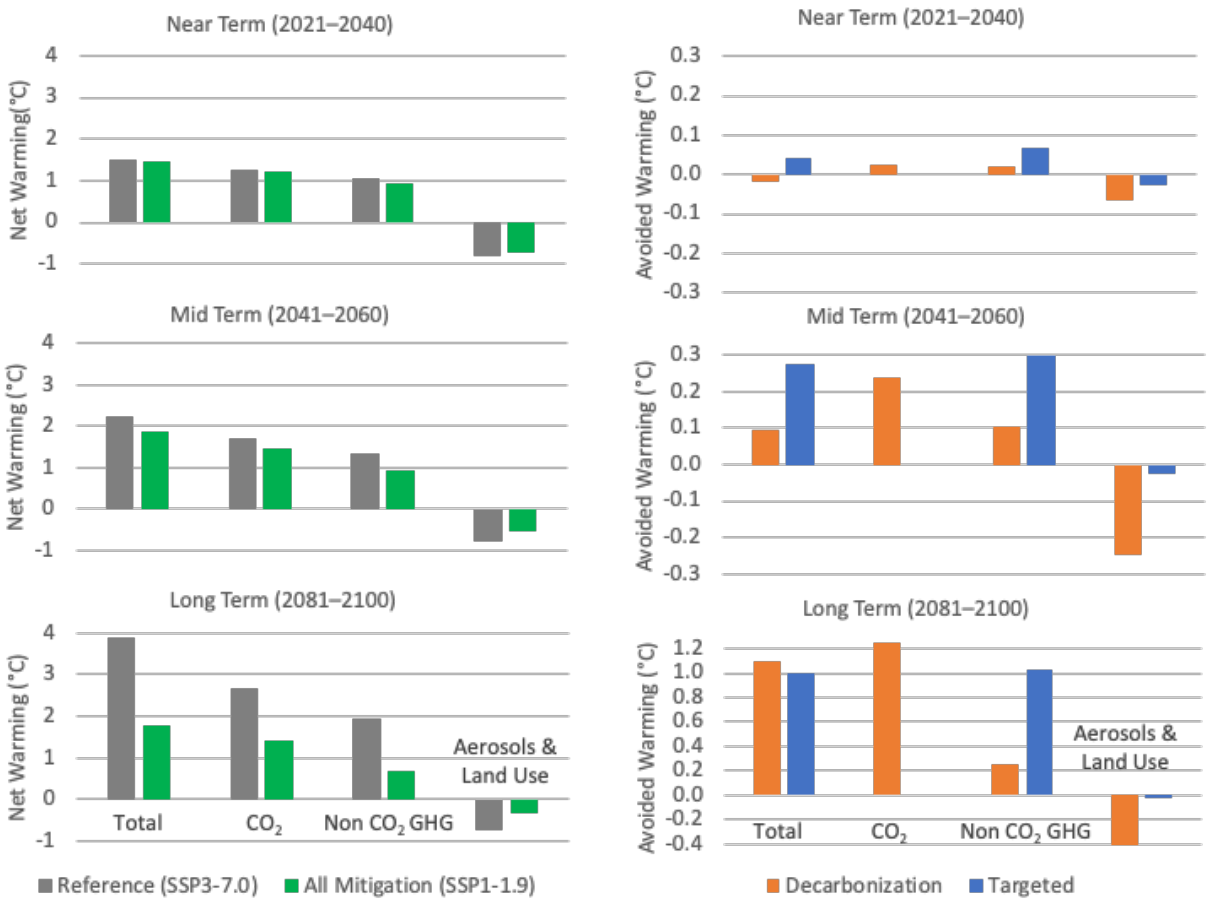

Figure S4. Left panel: net warming (negative means net cooling) relative to 1850 for reference (SSP3-7.0) and “decarb+targeted” mitigation (based on SSP1-1.9) scenarios (2) for all forcers (Total), CO_2, non-CO_2 GHG (includes methane, HFC, ozone, N_2O, CFC+HCFC), and aerosols (warming and cooling) and other (e.g., land use and solar) forcing. Right panel: avoided warming (negative values mean additional warming) relative to the reference scenario partitioned into decarbonization-driven and targeted mitigation contributions (see Table S5).

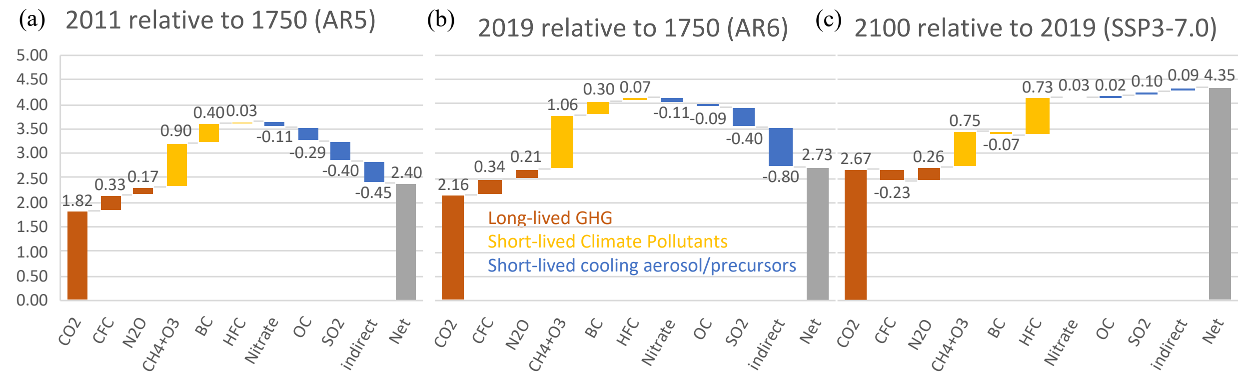

Figure S5. Bar chart version of Figure 1. Positive radiative forcing from long-lived GHG (orange), short-lived GHG, GHG-precursors and black carbon (BC; aerosol-radiation interaction and snow albedo effects only) (yellow), and negative forcing from individual aerosol direct effects (aerosol-radiation interaction) and the total aerosol indirect effects (aerosol-cloud interaction) (blue) in (a) 2011 relative to 1750, from AR5 (30), (b) 2019 relative to 1750, from AR6 (35). (c) The forcing at 2100 relative to 2019, under SSP3-7.0 emissions (2).

Table S1. Present-day radiative forcing of CO_2 and non-CO_2 GHG from various IPCC WGI reports and the climate model used in this study (RXM).

	Forcing (Wm^{-2})		Share of total GHG		Forcing (Wm^{-2})							
Source/ Period	CO_2	Non-CO_2	CO_2	Non-CO_2	LL GHG[a]	SL GHG[b]	CH_4	N_2O	CFC/ HCFC	HFC/ PFC/ SF_6	O_3	Note
RXM 2019–1750	1.85	1.57	54%	46%	2.33	1.09	0.63	0.18	0.30	0.06	0.40	This study using emissions from Hoesly et al. (2018) and SSP3-7.0 (Riahi et al 2017)
RXM 2011–1750	1.62	1.36	54%	46%	2.09	0.89	0.55	0.16	0.31	0.03	0.31	This study using emissions from Hoesly et al. (2018)
AR6 2019–1750	2.16	1.68	56%	44%	2.78	1.1	0.59	0.21	0.38	0.07	0.47	AR6 WGI Table 7.8; Table 7.5
AR5 2011–1750	1.82	1.43	56%	44%	2.32	0.93	0.55	0.17	0.33	0.03	0.35	Sum by concentration; Table 8. SM.6
AR5 2011–1750	1.68	1.57	52%	48%	2.03	1.2	0.97	0.17	0.18	0.03	0.22[c]	Sum by emission; Table 8. SM.6
AR4 2005–1750	1.66	1.35	55%	45%	2.14	0.9	0.55	0.16	0.32	0.017	0.3	AR4 WGI Figure TS.5; AR5 WGI Table 8.6
TAR 1998–1750	1.46	1.19	55%	45%	1.95	0.7	0.5	0.15	0.34	0	0.2	TAR WGI SPM p. 7
SAR 1993–1750	1.57	1.18	57%	43%	n/a	n/a	n/a	n/a	n/a	n/a	0.3	SAR WGI p. 109; AR5 WGI Table 8.6

[a] Long-lived greenhouse gas (LLGHG) includes CO_2, N_2O, CFC/HCFC
[b] Short-lived greenhouse gases (SLGHG) includes CH_4, HFC, tropospheric O_3
[c] Since ozone is not directly emitted, forcing here is taken as the sum of radiative forcing of precursor emissions of CO, NMVOC, NO_x.

Table S2. Historical radiative forcing of GHGs (excluding aerosols) from FF and non-FF sources.

	FF GHG	**non-FF GHG**	**FF (CO_2 + non-CO_2) & FOLU CO_2 GHG**	**Non-FF non-CO_2**	**Total GHG**	**Source**
2011–1750						**AR5 WGI Table 8.SM.6 sum by emissions partitioned based on Hoesly et al. (2018)**
Radiative forcing (Wm^{-2})	1.65	1.60	2.09	1.16	3.25	
Share of total	51% (38% CO_2; 13% non-CO_2)	49% (13% CO_2; 36% non-CO_2)	64% (51% CO_2; 13% non-CO_2)	36%	100%	
2011–1750						
Radiative forcing (Wm^{-2})	1.53	1.45	1.95	1.03	2.97	This study using Hoesly et al. (2018)
Share of total	51% (40% CO_2; 11% non-CO_2)	49% (14% CO_2; 35% non-CO_2)	65% (44% CO_2; 11% non-CO_2)	35%	100%	
2019–1750						AR6 WGI Table 7.5 and Table 7.8 (concentration-based) partitioned based on Hoesly et al. (2018) and Shindell and Smith (2019)
Radiative forcing (Wm^{-2})	2.07	1.81	2.58	1.30	3.88	
Share of total	53% (43% CO_2; 11% non-CO_2)	47% (13% CO_2; 34% non-CO_2)	66% (56% CO_2; 11% non-CO_2)	34%	100%	
2019–1750						This study using Hoesly et al. (2018) and Shindell and Smith (2019)
Radiative forcing (Wm^{-2})	1.81	1.61	2.24	1.18	3.42	
Share of total	53% (41% CO_2; 12% non-CO_2)	47% (13% CO_2; 34% non-CO_2)	66% (54% CO_2; 12% non-CO_2)	34%	100%	

Table S3. Radiative forcing (including GHG and aerosols) from FF and non-FF sources. Positive forcing from black carbon (BC) for 2011 is taken from IPCC AR5 WGI (0.64 Wm^{-2}) and scaled by the 55% fossil fuel share; the 2019 BC forcing is taken from IPCC AR6 WGI Chapter 7 (0.38 Wm^{-2} including aerosol-radiation interaction and snow albedo effect only) and scaled by 56% fossil fuel share. Negative forcing of cooling aerosol precursors is similarly scaled.

	FF	non-FF	FF (CO_2 + non-CO_2) & FOLU CO_2	non-FF non-CO_2	Total	Source
2011–1750						AR5 WGI Table 8.SM.6 sum by emissions partitioned based on Hoesly et al. (2018)
Radiative forcing (Wm^{-2})	1.0 (+2.0; –1.0)	1.6 (+1.9; –0.3)	1.5 (+2.5; –1.0)	1.1 (+1.4; –0.3)	2.6	
Share of total	39%	61%	56%	44%	100%	
2011–1750						This study using Hoesly et al., (2018)
Radiative forcing (Wm^{-2})	0.7 (+1.7; –1.0)	1.4 (+1.6; –0.2)	1.1 (+2.1; –1.0)	1.0 (+1.2; –0.2)	2.1	
Share of total	33%	67%	53%	47%	100%	
2019–1750						AR6 WGI Table 7.5, 7.8 (concentration-based) partitioned based on Hoesly et al. (2018) and Shindell and Smith (2019)
Radiative forcing (Wm^{-2})	0.9 (+2.3; –1.4)	1.7 (+2.0; –0.3)	1.4 (+2.8; –1.4)	1.2 (+1.5; –0.3)	2.7	
Share of total	34%	66%	54%	46%	100%	
2019–1750						This study using Hoesly et al. (2018) and Shindell and Smith (2019)
Radiative forcing (Wm^{-2})	1.0 (+2.1; –1.1)	1.6 (+1.8; –0.2)	1.4 (+2.5; –1.1)	1.2 (+1.4; –0.2)	2.6	
Share of total	39%	61%	55%	45%	100%	

Table S4. Simulated warming in 2015 relative to 1850 (°C) computed based on historical emissions partitioned into fossil fuel (FF) and non-FF sources.

	Total	**FF**	**non-FF**
CO_2	0.98	0.68	0.30
CH_4+O_3 + non-CH_4 O_3	0.52	0.19	0.34
BC (direct effects only)	0.37	0.20	0.16
HFC	0.02	-	0.02
CFC	0.17	-	0.17
N_2O	0.10	-	0.10
Total warming	2.15	**1.07**	**1.08**
Total cooling due to all aerosols (i.e., direct and indirect)	-1.15	**-0.88**	**-0.26**
Net	1.01	**0.19**	**0.82**

Table S5. Simulated future warming (avoided warming is shown as negative numbers) partitioned into "decarbonization-related" and "targeted" mitigation measures. These results are calculated using an average value of BC present-day direct forcing at 0.33 Wm^{-2} relative to pre-industrial. For comparison, IPCC AR6 WGI Chapter 6 (27) compares the "all measures" avoided warming for SSP3-7.0 and SSP1-1.9 and finds methane reductions avoid 0.07°C (-0.2 to 0.14°C) in 2040, which is comparable to the 0.09°C of avoided warming found in this study; and similarly for methane, ozone precursors and HFC AR6 finds 0.2°C (0.1 to 0.4°C) in 2040, which is comparable to the 0.18°C found in this study. AR6 finds methane, ozone precursor and HFC reductions of 0.8°C (0.5 to 1.3°C) in 2100, which is comparable to the 1.3°C found in this study, noting that we used the higher estimate for HFC abatement potential here.

Warming (ºC)	2030	2040	2050	2060	2100
Decarbonization					
CO_2	**-0.01**	**-0.08**	**-0.22**	**-0.42**	**-1.56**
SLCP	**-0.05**	**-0.14**	**-0.25**	**-0.34**	**-0.52**
BC	*-0.03*	*-0.09*	*-0.14*	*-0.19*	*-0.25*
CH4+O3	*-0.01*	*-0.03*	*-0.06*	*-0.09*	*-0.20*
non-CH4 O3	*-0.01*	*-0.03*	*-0.04*	*-0.06*	*-0.07*
Cooling Aerosols	0.09	0.24	0.39	0.51	0.66
Net	**0.03**	**0.02**	**-0.07**	**-0.25**	**-1.42**
Targeted measures					
SLCP	**-0.09**	**-0.20**	**-0.33**	**-0.48**	**-1.13**
BC	*-0.04*	*-0.07*	*-0.08*	*-0.09*	*-0.11*
CH4+O3	*-0.02*	*-0.06*	*-0.13*	*-0.20*	*-0.52*
non-CH4 O3	*-0.03*	*-0.05*	*-0.06*	*-0.08*	*-0.11*
HFCs	*0.00*	*-0.02*	*-0.06*	*-0.11*	*-0.39*
N_2O	-0.01	-0.02	-0.04	-0.06	-0.18
Cooling Aerosols	0.07	0.10	0.10	0.10	0.14
Net	**-0.03**	**-0.12**	**-0.26**	**-0.43**	**-1.17**
All measures					
CO_2	**-0.01**	**-0.08**	**-0.22**	**-0.42**	**-1.56**
SLCP	**-0.14**	**-0.34**	**-0.57**	**-0.81**	**-1.65**
BC	*-0.07*	*-0.15*	*-0.22*	*-0.28*	*-0.35*
CH4+O3	*-0.02*	*-0.09*	*-0.19*	*-0.30*	*-0.73*
non-CH4 O3	*-0.04*	*-0.07*	*-0.11*	*-0.13*	*-0.18*
HFCs	*0.00*	*-0.02*	*-0.06*	*-0.11*	*-0.39*
N_2O	-0.01	-0.02	-0.04	-0.06	-0.18
Cooling Aerosols	0.16	0.34	0.49	0.61	0.80
Net	**0.00**	**-0.10**	**-0.34**	**-0.68**	**-2.59**

Table S6a. Data shown in Figure 1.

Figure 1(a) 2011 v 1750 (AR5)				**Figure 1(b) 2019 v 1750 (AR6)**				**Figure 1(c) 2100 v 2019 (This study for SSP3-7.0)**		
	Wm^{-2}	Share total			Wm^{-2}	Share total			Wm^{-2}	Share total
$CH_4 + O_3$	0.90	25%		$CH_4 + O_3$	1.06	26%		Cooling aerosol	0.23	5%
BC	0.40	11%		BC	0.30	7%		$CH_4 + O_3$	0.75	16%
HFC	0.03	1%		HFC	0.07	2%		HFC	0.73	16%
CFC	0.33	9%		CFC	0.34	8%		N_2O	0.26	6%
N_2O	0.17	5%		N_2O	0.21	5%		CO_2	2.67	57%
CO_2	1.82	50%		CO_2	2.16	52%				
Total warming	**3.65**			**Total warming**	**4.13**			**Total warming**	**4.64**	
SO_2	-0.40	32%		SO_2	-0.40	29%		CFC	-0.23	77%
OC	-0.29	23%		OC	-0.09	6%		BC	-0.07	23%
Nitrate	-0.11	9%		Nitrate	-0.11	8%				
indirect	-0.45	36%		indirect	-0.80	57%				
Total cooling	**-1.25**			**Total cooling**	**-1.40**			**Total cooling**	**-0.29**	
Net	**2.40**			**Net**	**2.73**			**Net**	**4.35**	
Source: Table 8.SM.6; BC Table 8.4)				Source: AR6 WGI Table 7.8; Table 7.5; Figure 7.6; BC 7SM-6				Source: RXM for SSP3-7.0 avg BC		

Table S6b. Data shown in Figure 2.

Figure 2(a). Forcing in 2019 relative to 1750						**Figure 2(b). Forcing in 2100 relative to 2019**					
All CO_2 + non-CO_2 FF (Wm^{-2})			Non-FF non-CO_2 (Wm^{-2})			All CO_2 + non-CO_2 FF (Wm^{-2})			Non-FF non-CO_2 (Wm^{-2})		
CO_2 FF	1.41	57%	$CH_4 + O_3$	0.64	46%	CO_2 FF	2.74	85%	$CH_4 + O_3$	0.49	32%
CO_2 FOLU	0.43	17%	BC	0.20	15%	$CH_4 + O_3$	0.26	8%	HFC	0.73	49%
$CH_4 + O_3$	0.39	16%	HFC	0.06	4%	Cooling aerosol	0.22	7%	N_2O	0.26	17%
BC	0.25	10%	CFC	0.30	22%				Cooling Aerosol	0.02	1%
			N_2O	0.18	13%						
Total warming	**2.49**		**Total warming**	**1.38**		**Total warming**	**3.22**		**Total warming**	**1.50**	
Total cooling	**-1.06**		**Total cooling**	**-0.22**		**Total cooling**	**-0.12**		**Total cooling**	**-0.25**	
Cooling aerosol	-1.06		Cooling aerosol	-0.22		CO_2 FOLU	-0.07		BC	-0.02	
						BC	-0.05		CFC	-0.23	
Net	**1.43**		**Net**	**1.16**		**Net**	**3.10**		**Net**	**1.25**	