14 Perspectives on Climate Change Mitigation

KEY FINDINGS

1. Reducing net emissions of CO_2 is necessary to limit near-term climate change and long-term warming. Other greenhouse gases (for example, methane) and black carbon aerosols exert stronger warming effects than CO_2 on a per ton basis, but they do not persist as long in the atmosphere; therefore, mitigation of non-CO_2 species contributes substantially to near-term cooling benefits but cannot be relied upon for ultimate stabilization goals. (*Very high confidence*)

2. Stabilizing global mean temperature to less than 3.6°F (2°C) above preindustrial levels requires substantial reductions in net global CO_2 emissions prior to 2040 relative to present-day values and likely requires net emissions to become zero or possibly negative later in the century. After accounting for the temperature effects of non-CO_2 species, cumulative global CO_2 emissions must stay below about 800 GtC in order to provide a two-thirds likelihood of preventing 3.6°F (2°C) of warming. Given estimated cumulative emissions since 1870, no more than approximately 230 GtC may be emitted in the future to remain under this temperature threshold. Assuming global emissions are equal to or greater than those consistent with the RCP4.5 scenario, this cumulative carbon threshold would be exceeded in approximately two decades. (*High confidence*)

3. Achieving global greenhouse gas emissions reductions before 2030 consistent with targets and actions announced by governments in the lead up to the 2015 Paris climate conference would hold open the possibility of meeting the long-term temperature goal of limiting global warming to 3.6°F (2°C) above preindustrial levels, whereas there would be virtually no chance if net global emissions followed a pathway well above those implied by country announcements. Actions in the announcements are, by themselves, insufficient to meet a 3.6°F (2°C) goal; the likelihood of achieving that goal depends strongly on the magnitude of global emissions reductions after 2030. (*High confidence*)

4. Further assessments of the technical feasibilities, costs, risks, co-benefits, and governance challenges of climate intervention or geoengineering strategies, which are as yet unproven at scale, are a necessary step before judgments about the benefits and risks of these approaches can be made with high confidence. (*High confidence*)

Recommended Citation for Chapter

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Introduction

This chapter provides scientific context for key issues regarding the long-term mitigation of climate change. As such, this chapter first addresses the science underlying the timing of when and how CO_2 and other greenhouse gas (GHG) mitigation activities that occur in the present affect the climate of the future. When do we see the benefits of a GHG emission reduction activity? Chapter 4: Projections provides further context for this topic. Relatedly, the present chapter discusses the significance of the relationship between net cumulative CO_2 emissions and eventual global warming levels. The chapter reviews recent analyses of global emissions pathways associated with preventing 3.6°F (2°C) or 2.7°F (1.5°C) of warming relative to preindustrial times. And finally, this chapter briefly reviews the status of climate intervention proposals and how these types of mitigation actions could possibly play a role in avoiding future climate change.

14.1 The Timing of Benefits from Mitigation Actions

14.1.1 Lifetime of Greenhouse Gases and Inherent Delays in the Climate System

Carbon dioxide (CO_2) concentrations in the atmosphere are directly affected by human activities in the form of CO_2 emissions. Atmospheric CO_2 concentrations adjust to human emissions of CO_2 over long time scales, spanning from decades to millennia.[1, 2] The IPCC estimated that 15% to 40% of CO_2 emitted until 2100 will remain in the atmosphere longer than 1,000 years.[1] The persistence of warming is longer than the atmospheric lifetime of CO_2 and other GHGs, owing in large part to the thermal inertia of the ocean.[3] Climate change resulting from anthropogenic CO_2 emissions, and any associated risks to the environment, human health and society, are thus essentially irreversible on human timescales.[4] The world is committed to some degree of irreversible warming and associated climate change resulting from emissions to date.

The long lifetime in the atmosphere of CO_2[2] and some other key GHGs, coupled with the time lag in the response of the climate system to atmospheric forcing,[5] has timing implications for the benefits (i.e., avoided warming or risk) of mitigation actions. Large reductions in emissions of the long-lived GHGs are estimated to have modest temperature effects in the *near term* (e.g., over one to two decades) because total atmospheric concentration levels require long periods to adjust,[6] but are necessary in the *long term* to achieve any objective of preventing warming of any desired magnitude. Near-term projections of global mean surface temperature are therefore not strongly influenced by changes in near-term emissions but rather dominated by natural variability, the Earth system response to past and current GHG emissions, and by model spread (i.e., the different climate outcomes associated with different models using the same emissions pathway).[7] Long-term projections of global surface temperature (after mid-century), on the other hand, show that the choice of global emissions pathway, and thus the long-term mitigation pathway the world chooses, is the dominant source of future uncertainty in climate outcomes.[3, 8]

Some studies have nevertheless shown the potential for some near-term benefits of mitigation. For example, one study found that, even at the regional scale, heat waves would already be significantly more severe by the 2030s in a non-mitigation scenario compared to a moderate mitigation scenario.[9] The mitigation of non-CO_2 GHGs with short atmospheric lifetimes (such as methane, some hydrofluorocarbons [HFCs], and ozone) and black carbon (an aerosol that absorbs solar radiation; see Ch. 2: Physical Drivers of Climate Change), collectively referred to as short-lived climate pollutants

(SLCPs), has been highlighted as a particular way to achieve more rapid climate benefits (e.g., Zaelke and Borgford-Parnell 2015[10]). SLCPs are substances that not only have an atmospheric lifetime shorter (for example, weeks to a decade) than CO_2 but also exert a stronger radiative forcing (and hence temperature effect) compared to CO_2 on a per ton basis.[11] For these reasons, mitigation of SLCP emissions produces more rapid radiative responses. In the case of black carbon, with an atmospheric lifetime of a few days to weeks,[12] emissions (and therefore reductions of those emissions) produce strong regional effects. Mitigation of black carbon and methane also generate direct health co-benefits.[13, 14] Reductions and / or avoidances of SLCP emissions could be a significant contribution to staying at or below a 3.6°F (2°C) increase or any other chosen global mean temperature increase.[15, 16, 17, 18] The recent Kigali Amendment to the Montreal Protocol seeks to phase down global HFC production and consumption in order to avoid substantial GHG emissions in coming decades. Stringent and continuous SLCP mitigation could potentially increase allowable CO_2 budgets for avoiding warming beyond any desired future level, by up to 25% under certain scenarios.[18] However, given that economic and technological factors tend to couple CO_2 and many SLCP emissions to varying degrees, significant SLCP emissions reductions would be a co-benefit of CO_2 mitigation.

14.1.2 Stock and Stabilization: Cumulative CO_2 and the Role of Other Greenhouse Gases

Net cumulative CO_2 emissions in the industrial era will largely determine long-term, global mean temperature change. A robust feature of model climate change simulations is a nearly linear relationship between cumulative CO_2 emissions and global mean temperature increases, irrespective of the details and exact timing of the emissions pathway (see Figure 14.1; see also Ch. 4: Projections). Limiting and stabilizing warming to any level implies that there is a physical upper limit to the cumulative amount of CO_2 that can be added to the atmosphere.[3] Eventually stabilizing the global temperature requires CO_2 emissions to approach zero.[19] Thus, for a 3.6°F (2°C) or any desired global mean warming goal, an estimated range of cumulative CO_2 emissions from the current period onward can be calculated. The key sources of uncertainty for any compatible, forward looking CO_2 budget associated with a given future warming objective include the climate sensitivity, the response of the carbon cycle including feedbacks (for example, the release of GHGs from permafrost thaw), the amount of past CO_2 emissions, and the influence of past and future non-CO_2 species.[3, 19] Increasing the probability that any given temperature goal will be reached therefore implies tighter constraints on cumulative CO_2 emissions. Relatedly, for any given cumulative CO_2 budget, higher emissions in the near term imply the need for steeper reductions in the long term.

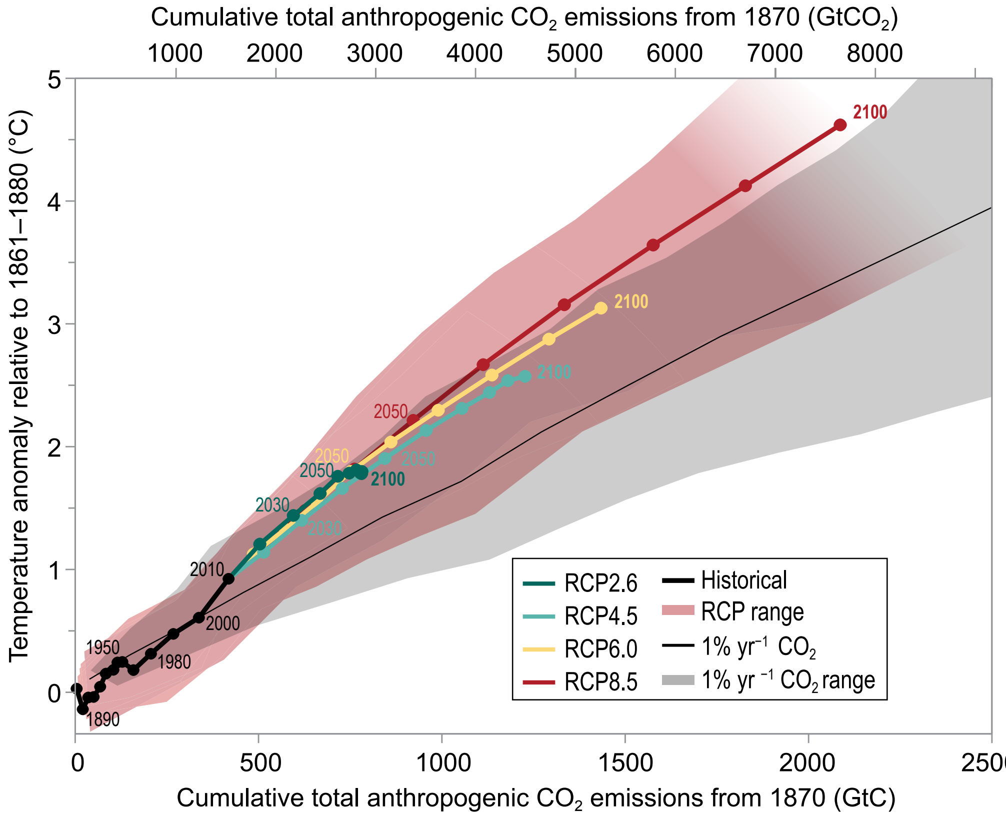

Figure 14.1: Global mean temperature change for a number of scenarios as a function of cumulative CO_2 emissions from preindustrial conditions, with time progressing along each individual line for each scenario. (Figure source: IPCC 2013;[42] ©IPCC. Used with permission).

Between 1870 and 2015, human activities, primarily the burning of fossil fuels and deforestation, emitted about 560 GtC in the form of CO_2 into the atmosphere.[20] According to best estimates in the literature, 1,000 GtC is the total cumulative amount of CO_2 that could be emitted yet still provide a two-thirds likelihood of preventing 3.6°F (2°C) of global mean warming since preindustrial times.[3, 21] That estimate, however, ignores the additional radiative forcing effects of non-CO_2 species (that is, the net positive forcing resulting from the forcing of other well-mixed GHGs, including halocarbons, plus the other ozone precursor gases and aerosols). Considering both historical and projected non-CO_2 effects reduces the estimated cumulative CO_2 budget compatible with any future warming goal,[18] and in the case of 3.6°F (2°C) it reduces the aforementioned estimate to 790 GtC.[3] Given this more comprehensive estimate, limiting the global average temperature increase to below 3.6°F (2°C) means approximately 230 GtC more CO_2 could be emitted globally. To illustrate, if one assumes future global emissions follow a pathway consistent with the lower scenario (RCP4.5), this cumulative carbon threshold is exceeded by around 2037, while under the higher scenario (RCP8.5) this occurs by around 2033. To limit the global average temperature increase to 2.7°F (1.5°C), the estimated cumulative CO_2 budget is about 590 GtC (assuming linear scaling with the compatible 3.6°F (2°C) budget that also considers non-CO_2 effects), meaning only about 30 GtC more of CO_2 could be emitted. Further emissions of 30 GtC (in the form of CO_2) are projected to occur in the next few years (Table 14.1).

Table 14.1: Dates illustrating when cumulative CO_2 emissions thresholds associated with eventual warming of 3.6°F or 2.7°F above preindustrial levels might be reached. RCP4.5 and RCP8.5 refer, respectively, to emissions consistent with the lower and higher scenarios used throughout this report. The estimated cumulative CO_2 emissions (measured in Gigatons (Gt) of carbon) associated with different probabilities (e.g., 66%) of preventing 3.6°F (2°C) of warming are from the IPCC.[3] The cumulative emissions compatible with 2.7°F (1.5°C) are linearly derived from the estimates associated with 3.6°F (2°C). The cumulative CO_2 estimates take into account the additional net warming effects associated with past and future non-CO_2 emissions consistent with the RCP scenarios. Historical CO_2 emissions from 1870–2015 (including fossil fuel combustion, land use change, and cement manufacturing) are from Le Quéré et al.[20] See Traceable Accounts for further details.

	Dates by when cumulative carbon emissions (GtC) since 1870 reach amount commensurate with 3.6°F (2°C), when accounting for non-CO_2 forcings		
	66% = 790 GtC	50% = 820 GtC	33% = 900 GtC
RCP4.5	2037	2040	2047
RCP8.5	2033	2035	2040
	Dates by when cumulative carbon emissions (GtC) since 1870 reach amount commensurate with 2.7°F (1.5°C), when accounting for non-CO_2 forcings		
	66% = 593 GtC	50% = 615 GtC	33% = 675 GtC
RCP4.5	2019	2021	2027
RCP8.5	2019	2021	2025

14.2 Pathways Centered Around 3.6°F (2°C)

The idea of a 3.6°F (2°C) goal can be found in the scientific literature as early as 1975. Nordhaus[22] justified it by simply stating, "If there were global temperatures more than 2 or 3°C above the current average temperature, this would take the climate outside of the range of observations which have been made over the last several hundred thousand years." Since that time, the concept of a 3.6°F (2°C) goal gained attention in both scientific and policy discourse. For example, the Stockholm Environment Institute[23] published a report stating that 3.6°F (2°C) "can be viewed as an upper limit beyond which the risks of grave damage to ecosystems, and of non-linear responses, are expected to increase rapidly." And in 2007, the IPCC Fourth Assessment Report stated, among other things: "Confidence has increased that a 1 to 2°C increase in global mean temperature above 1990 levels (about 1.5 to 2.5°C above pre-industrial) poses significant risks to many unique and threatened systems including many biodiversity hotspots." Most recently, the Paris Agreement of 2015 took on the long-term goal of "holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels." Many countries announced GHG emissions reduction targets and related actions (formally called Intended Nationally Determined Contributions [INDCs]) in the lead up to the Paris meeting; these announcements addressed emissions through 2025 or 2030 and take a wide range of forms. A number of studies have generated projections of future GHG emissions based on these announcements and evaluated whether, if implemented, the resulting emissions reductions would limit the increase in global average temperatures to 3.6°F (2°C) above preindustrial levels. In June 2017, the United States announced its intent to withdraw from the Paris Agreement. The scenarios assessed below were published prior to this announcement and therefore do not reflect the implications of this announcement.

Estimates of global emissions and temperature implications from emissions pathways consistent with targets and actions announced by governments in the lead up to the 2015 Paris climate conference[24, 25, 26, 27, 28] generally find that 1) these targets and actions would reduce GHG emissions growth by 2030 relative to a situation where these goals did not exist, though emissions are still not expected to be lower in 2030 than in 2015; and 2) the targets and actions would be a step towards limiting global mean temperature increase to 3.6°F (2°C), but by themselves, would be insufficient for this goal. According to one study, emissions pathways consistent with governments' announcements imply a median warming of 4.7°–5.6°F (2.6°–3.1°C) by 2100, though year 2100 temperature estimates depend on assumed emissions between 2030 and 2100.[24] For example, Climate Action Tracker,[26] using alternative post-2030 assumptions, put the range at 5.9°–7.0°F (3.3°–3.9°C).

Emissions pathways consistent with the targets and actions announced by governments in the lead up to the 2015 Paris conference have been evaluated in the context of the likelihood of global mean surface temperature change (Figure 14.2). It was found that the likelihood of limiting the global mean temperature increase to 3.6°F (2°C) or less was enhanced by these announced actions, but depended strongly on assumptions about subsequent policies and measures. Under a scenario in which countries maintain the same pace of decarbonization past 2030 as they announced in their first actions (leading up to 2025 or 2030) there is some likelihood (less than 10%) of preventing a global mean surface temperature change of 3.6°F (2°C) relative to preindustrial levels; this scenario thus holds open the possibility of achieving this goal, whereas there would be virtually no chance if emissions climbed to levels above those implied by country announcements (Figure 14.2).[27] Greater emissions reductions beyond 2030 (based on higher decarbonization rates past 2030) increase the likelihood of limiting warming to 3.6°F (2°C) or lower to about 30%, and almost eliminate the likelihood of a global mean temperature increase greater than 7°F (4°C). Scenarios that assume even greater emissions reductions past 2030 would be necessary to have at least a 50% probability of limiting warming to 3.6°F (2°C)[27] as discussed and illustrated further below.

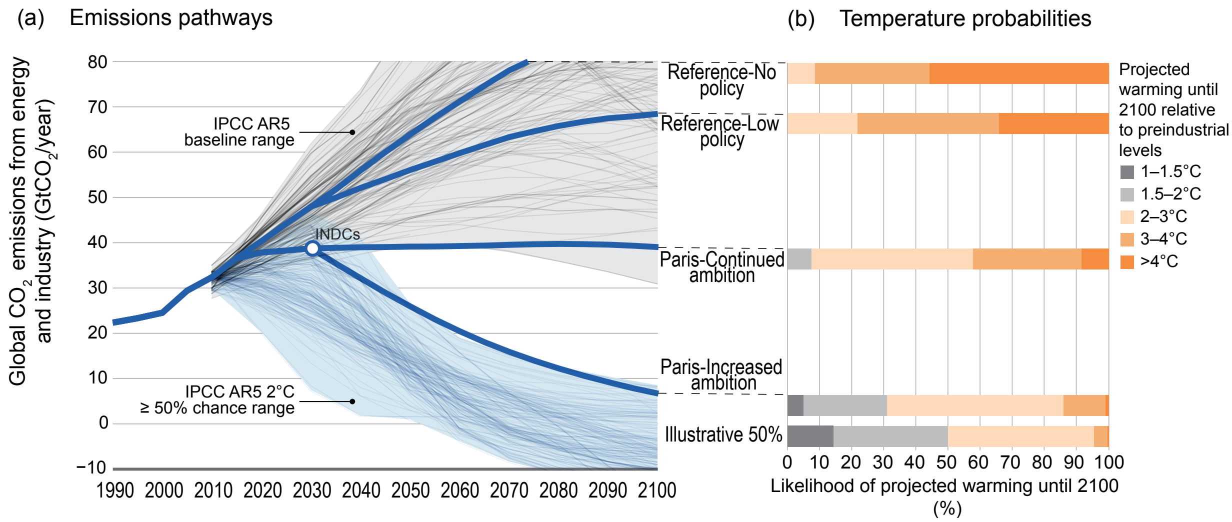

Figure 14.2: Global CO_2 emissions and probabilistic temperature outcomes of government announcements associated with the lead up to the Paris climate conference. (a) Global CO_2 emissions from energy and industry (includes CO_2 emissions from all fossil fuel production and use and industrial processes such as cement manufacture that also produce CO_2 as a byproduct) for emissions pathways following no policy, current policy, meeting the governments' announcements with constant country decarbonization rates past 2030, and meeting the governments' announcements with higher rates of decarbonization past 2030. INDCs refer to Intended Nationally Determined Contributions which is the term used for the governments' announced actions in the lead up to Paris. (b) Likelihoods of different levels of increase in global mean surface temperature during the 21st century relative to preindustrial levels for the four scenarios. Although (a) shows only CO_2 emissions from energy and industry, temperature outcomes are based on the full suite of GHG, aerosol, and short-lived species emissions across the full set of human activities and physical Earth systems. (Figure source: Fawcett et al. 2015[27]).

There is a limited range of pathways which enable the world to remain below 3.6°F (2°C) of warming (see Figure 14.3), and almost all but the most rapid near-term mitigation pathways are heavily reliant on the implementation of CO_2 removal from the atmosphere later in the century or other climate intervention, discussed below. If global emissions are in line with the first round of announced government actions by 2030, then the world likely needs to reduce effective GHG emissions to zero by 2080 and be significantly net negative by the end of the century (relying on as yet unproven technologies to remove GHGs from the atmosphere) in order to stay below 3.6°F (2°C) of warming. Avoiding 2.7°F (1.5°C) of warming requires more aggressive action still, with net zero emissions achieved by 2050 and net negative emissions thereafter. In either case, faster near-term emissions reductions significantly decrease the requirements for net negative emissions in the future.

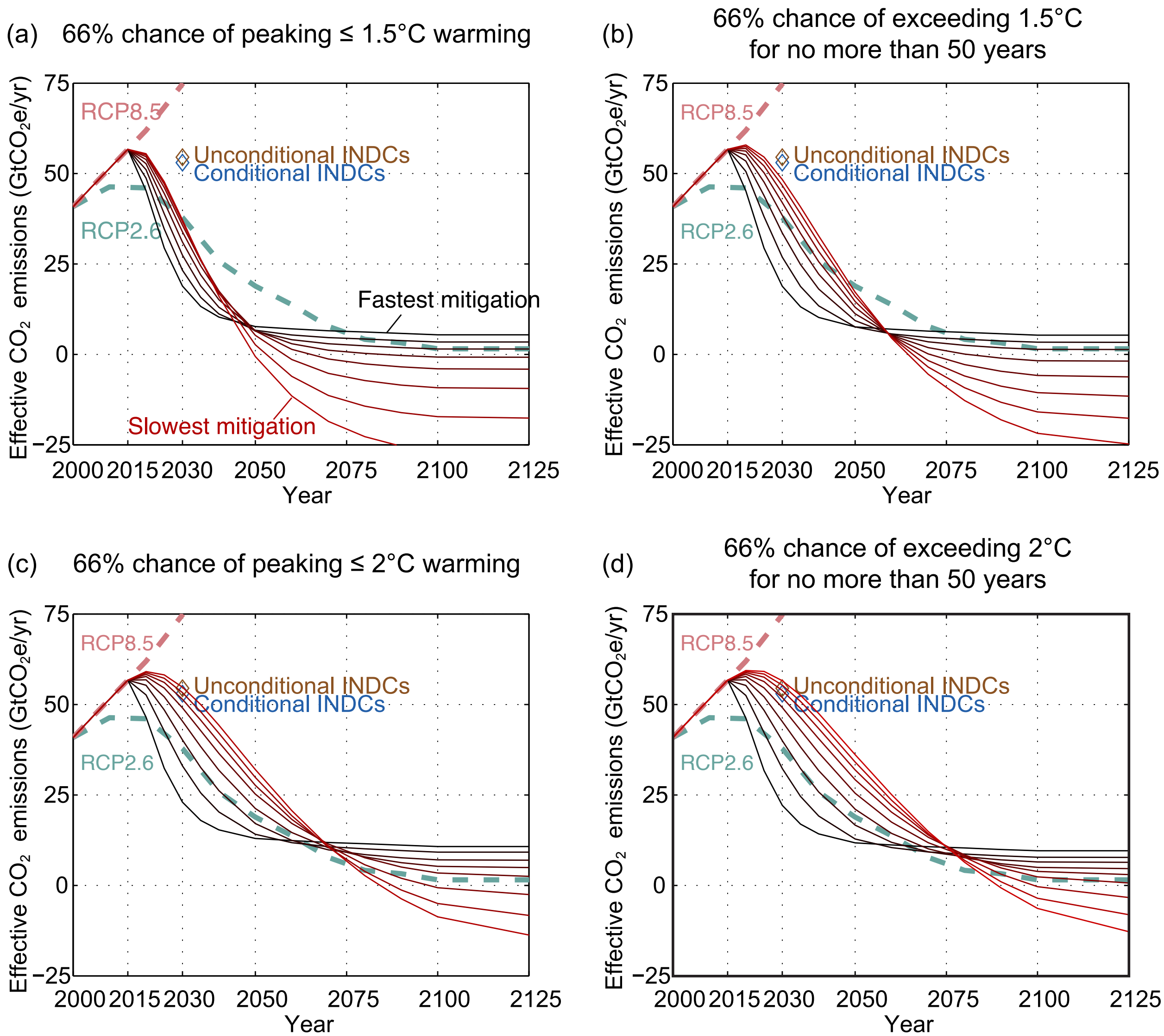

Figure 14.3: Global emissions pathways for GHGs, expressed as CO_2-equivalent emissions, which would be consistent with different temperature goals (relative to preindustrial temperatures). INDCs refer to Intended Nationally Determined Contributions which is the term used for the governments' announced actions in the lead up to Paris. (a) shows a set of pathways where global mean temperatures would likely (66%) not exceed 2.7°F (1.5°C). A number of pathways are consistent with the goal, ranging from the red curve (slowest near-term mitigation with large negative emissions requirements in the future) to the black curve with rapid near-term mitigation and less future negative emissions. (b) shows similar pathways with a 66% chance of exceeding 2.7°F (1.5°C) for only 50 years, where (c) and (d) show similar emission pathways for 3.6°F (2°C). (Figure source: Sanderson et al. 2016[25]).

14.3 The Potential Role of Climate Intervention in Mitigation Strategies

Limiting the global mean temperature increase through emissions reductions or adapting to the impacts of a greater-than-3.6°F (2°C) warmer world have been acknowledged as severely challenging tasks by the international science and policy communities. Consequently, there is increased interest by some scientists and policy makers in exploring additional measures designed to reduce net radiative forcing through other, as yet untested actions, which are often referred to as geoengineering or climate intervention (CI) actions. CI approaches are generally divided into two categories: carbon dioxide removal (CDR)[29] and solar radiation management (SRM).[30] CDR and SRM methods may have future roles in helping meet global temperature goals. Both methods would reduce global average temperature by reducing net global radiative forcing: CDR through reducing atmospheric CO_2 concentrations and SRM through increasing Earth's albedo.

The evaluation of the suitability and advisability of potential CI actions requires a decision framework that includes important dimensions beyond scientific and technical considerations. Among these dimensions to be considered are the potential development of global and national governance and oversight procedures, geopolitical relations, legal considerations, environmental, economic and societal impacts, ethical considerations, and the relationships to global climate policy and current GHG mitigation and adaptation actions. It is clear that these social science and other non-physical science dimensions are likely to be a major part of the decision framework and ultimately control the adoption and effectiveness of CI actions. This report only acknowledges these mostly non-physical scientific dimensions and must forego a detailed discussion.

By removing CO_2 from the atmosphere, CDR directly addresses the principal cause of climate change. Potential CDR approaches include direct air capture, currently well-understood biological methods on land (for example, afforestation), less well-understood and potentially risky methods in the ocean (for example, ocean fertilization), and accelerated weathering (for example, forming calcium carbonate on land or in the oceans).[29] While CDR is technically possible, the primary challenge is achieving the required scale of removal in a cost-effective manner, which in part presumes a comparison to the costs of other, more traditional GHG mitigation options.[31, 32] In principle, at large scale, CDR could measurably reduce CO_2 concentrations (that is, cause negative emissions). Point-source capture (as opposed to CO_2 capture from ambient air) and removal of CO_2 is a particularly effective CDR method. The climate value of avoided CO_2 emissions is essentially equivalent to that of the atmospheric removal of the same amount. To realize sustained climate benefits from CDR, however, the removal of CO_2 from the atmosphere must be essentially permanent—at least several centuries to millennia. In addition to high costs, CDR has the additional limitation of long implementation times.

By contrast, SRM approaches offer the only known CI methods of cooling Earth within a few years after inception. An important limitation of SRM is that it would not address damage to ocean ecosystems from increasing ocean acidification due to continued CO_2 uptake. SRM could theoretically have a significant global impact even if implemented by a small number of nations, and by nations that are not also the major emitters of GHGs; this could be viewed either as a benefit or risk of SRM.[30]

Proposed SRM concepts increase Earth's albedo through injection of sulfur gases or aerosols into the stratosphere (thereby simulating the effects of explosive volcanic eruptions) or marine cloud brightening through aerosol injection near the ocean surface. Injection of solid particles is an alternative to sulfur and yet other SRM methods could be deployed in space. Studies have evaluated the expected effort and effectiveness of various SRM methods.[30, 33] For example, model runs were performed in the GeoMIP project using the full CMIP5 model suite to illustrate the effect of reducing top-of-the-atmosphere insolation to offset climate warming from CO_2.[34] The idealized runs, which assumed an abrupt, globally-uniform insolation reduction in a 4 × CO_2 atmosphere, show that temperature increases are largely offset, most sea ice loss is avoided, average precipitation changes are small, and net primary productivity increases. However, important regional changes in climate variables are likely in SRM scenarios as discussed below.

As global ambitions increase to avoid or remove CO_2 emissions, probabilities of large increases in global temperatures by 2100 are proportionately reduced.[27] Scenarios in which large-scale CDR is used to meet a 3.6°F (2°C) limit while allowing business-as-usual consumption of fossil fuels are likely not feasible with present technologies. Model SRM scenarios have been developed that show reductions in radiative forcing up to 1 W/m^2 with annual stratospheric injections of 1 Mt of sulfur from aircraft or other platforms.[35, 36] Preliminary studies suggest that this could be accomplished at an implementation cost as low as a few billion dollars per year using current technology, enabling an individual country or subnational entity to conduct activities having significant global climate impacts.

SRM scenarios could in principle be designed to follow a particular radiative forcing trajectory, with adjustments made in response to monitoring of the climate effects.[37] SRM could be used as an interim measure to avoid peaks in global average temperature and other climate parameters. The assumption is often made that SRM measures, once implemented, must continue indefinitely in order to avoid the rapid climate change that would occur if the measures were abruptly stopped. SRM could be used, however, as an interim measure to buy time for the implementation of emissions reductions and/or CDR, and SRM could be phased out as emissions reductions and CDR are phased in, to avoid abrupt changes in radiative forcing.[37]

SRM via marine cloud brightening derives from changes in cloud albedo from injection of aerosols into low-level clouds, primarily over the oceans. Clouds with smaller and more numerous droplets reflect more sunlight than clouds with fewer and larger droplets. Current models provide more confidence in the effects of stratospheric injection than in marine cloud brightening and in achieving scales large enough to reduce global forcing.[30]

CDR and SRM have substantial uncertainties regarding their effectiveness and unintended consequences. For example, CDR on a large scale may disturb natural systems and have important implications for land-use changes. For SRM actions, even if the reduction in global average radiative forcing from SRM was exactly equal to the radiative forcing from GHGs, the regional and temporal patterns of these forcings would have important differences. While SRM could rapidly lower global mean temperatures, the effects on precipitation patterns, light availability, crop yields, acid rain, pollution levels, temperature gradients, and atmospheric circulation in response to such actions are less well understood. Also, the reduction in sunlight from SRM may have effects on agriculture and ecosystems. In general, restoring regional preindustrial temperature and precipitation conditions through

SRM actions is not expected to be possible based on ensemble modeling studies.[38] As a consequence, optimizing the climate and geopolitical value of SRM actions would likely involve tradeoffs between regional temperature and precipitation changes.[39] Alternatively, intervention options have been proposed to address particular regional impacts.[40]

GHG forcing has the potential to push the climate farther into unprecedented states for human civilization and increase the likelihood of "surprises" (see Ch. 15: Potential Surprises). CI could prevent climate change from reaching a state with more unpredictable consequences. The potential for rapid changes upon initiation (or ceasing) of a CI action would require adaptation on timescales significantly more rapid than what would otherwise be necessary. The NAS[29, 30] and the Royal Society[41] recognized that research on the feasibilities and consequences of CI actions is incomplete and call for continued research to improve knowledge of the feasibility, risks, and benefits of CI techniques.

TRACEABLE ACCOUNTS

Key Finding 1

Reducing net emissions of CO_2 is necessary to limit near-term climate change and long-term warming. Other greenhouse gases (for example, methane) and black carbon aerosols exert stronger warming effects than CO_2 on a per ton basis, but they do not persist as long in the atmosphere; therefore, mitigation of non-CO_2 species contributes substantially to near-term cooling benefits but cannot be relied upon for ultimate stabilization goals. (*Very high confidence*)

Description of evidence base

Joos et al.[2] and Ciais et al. (see Box 6.1 in particular)[1] describe the climate response of CO_2 pulse emissions, and Solomon et al.,[4] NRC,[19] and Collins et al.[3] describe the long-term warming and other climate effects associated with CO_2 emissions. Paltsev et al.[8] and Collins et al.[3] describe the near-term vs. long-term nature of climate outcomes resulting from GHG mitigation. Myhre et al.[11] synthesize numerous studies detailing information about the radiative forcing effects and atmospheric lifetimes of all GHGs and aerosols (see in particular Appendix 8A therein). A recent body of literature has emerged highlighting the particular role that non-CO_2 mitigation can play in providing near-term cooling benefits (e.g., Shindell et al. 2012;[17] Zaelke and Borgford-Parnell 2015;[10] Rogelj et al. 2015[18]). For each of the individual statements made in Key Finding 1, there are numerous literature sources that provide consistent grounds on which to make these statements with *very high confidence*.

Major uncertainties

The Key Finding is comprised of qualitative statements that are traceable to the literature described above and in this chapter. Uncertainties affecting estimates of the exact timing and magnitude of the climate response following emissions (or avoidance of those emissions) of CO_2 and other GHGs involve the quantity of emissions, climate sensitivity, some uncertainty about the removal time or atmospheric lifetime of CO_2 and other GHGs, and the choice of model carrying out future simulations. The role of black carbon in climate change is more uncertain compared to the role of the well-mixed GHGs (see Bond et al. 2013[12]).

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Key Finding 1 is comprised of qualitative statements based on a body of literature for which there is a high level of agreement. There is a well-established understanding, based in the literature, of the atmospheric lifetime and warming effects of CO_2 vs. other GHGs after emission, and in turn how atmospheric concentration levels respond following the emission of CO_2 and other GHGs.

Summary sentence or paragraph that integrates the above information

The qualitative statements contained in Key Finding 1 reflect aspects of fundamental scientific understanding, well grounded in the literature, that provide a relevant framework for considering the role of CO_2 and non-CO_2 species in mitigating climate change.

Key Finding 2

Stabilizing global mean temperature to less than 3.6°F (2°C) above preindustrial levels requires substantial reductions in net global CO_2 emissions prior to 2040 relative to present-day values and likely requires net emissions to become zero or possibly negative later in the century. After accounting for the temperature effects of non-CO_2 species, cumulative global CO_2 emissions must stay below about 800 GtC in order to provide a two-thirds likelihood of preventing 3.6°F (2°C) of warming. Given estimated cumulative emissions since 1870, no more than approximately 230 GtC may be emitted in the future to remain under this temperature threshold. Assuming global emissions are equal to or greater than those consistent with the RCP4.5 scenario, this cumulative carbon threshold would be exceeded in approximately two decades. (*High confidence*)

Description of evidence base

Key Finding 2 is a case study, focused on a pathway associated with 3.6°F (2°C) of warming, based on the more general concepts described in the chapter. As such, the evidence for the relationship between cumulative CO_2 emissions and global mean temperature response[3, 19, 21] also supports Key Finding 3.

Numerous studies have provided best estimates of cumulative CO_2 compatible with 3.6°F (2°C) of warming above preindustrial levels, including a synthesis by the IPCC.[3] Sanderson et al.[25] provide further recent evidence to support the statement that net CO_2 emissions would need to approach zero or become negative later in the century in order to avoid this level of warming. Rogelj et al. 2015[18] and the IPCC[3] demonstrate that the consideration of non-CO_2 species has the effect of further constraining the amount of cumulative CO_2 emissions compatible with 3.6°F (2°C) of warming.

Table 14.1 shows the IPCC estimates associated with different probabilities (66% [the one highlighted in Key Finding 2], 50%, and 33%) of cumulative CO_2 emissions compatible with warming of 3.6°F (2°C) above preindustrial levels, and the cumulative CO_2 emissions compatible with 2.7°F (1.5°C) are in turn linearly derived from those, based on the understanding that cumulative emissions scale linearly with global mean temperature response. The IPCC estimates take into account the additional radiative forcing effects—past and future—of non-CO_2 species based on the emissions pathways consistent with the RCP scenarios (available here: https://tntcat.iiasa.ac.at/RcpDb/dsd?Action=htmlpage&page=about#descript).

The authors calculated the dates shown in Table 14.1, which supports the last statement in Key Finding 2, based on Le Quéré et al.[20] and the publicly available RCP database. Le Quéré et al.[20] provide the widely used reference for historical global, annual CO_2 emissions from 1870 to 2015 (land-use change emissions were estimated up to year 2010 so are assumed to be constant between 2010 and 2015). Future CO_2 emissions are based on the lower and higher scenarios (RCP4.5 and RCP8.5, respectively); annual numbers between model-projected years (2020, 2030, 2040, etc.) are linearly interpolated.

Major uncertainties

There are large uncertainties about the course of future CO_2 and non-CO_2 emissions, but the fundamental point that CO_2 emissions need to eventually approach zero or possibly become net negative to stabilize warming below 3.6°F (2°C) holds regardless of future emissions scenario. There are also large uncertainties about the magnitude of past (since 1870 in this case) CO_2 and non-CO_2 emissions, which in turn influence the uncertainty about compatible cumulative emissions from the present day forward. Further uncertainties regarding non-CO_2 species, including aerosols, include their radiative forcing effects. The uncertainty in achieving the temperature targets for a given emissions pathway is, in large part, reflected by the range of probabilities shown in Table 14.1.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

There is *very high* confidence in the first statement of Key Finding 2 because it is based on a number of sources with a high level of agreement. The role of non-CO_2 species in particular introduces uncertainty in the second statement of Key Finding 2 regarding compatible cumulative CO_2 emissions that take into account past and future radiative forcing effects of non-CO_2 species; though this estimate is based on a synthesis of numerous studies by the IPCC. The last statement of Key Finding 2 is straightforward based on the best available estimates of historical emissions in combination with the widely used future projections of the RCP scenarios.

Summary sentence or paragraph that integrates the above information

Fundamental scientific understanding of the climate system provides a framework for considering potential pathways for achieving a target of preventing 3.6°F (2°C) of warming. There are uncertainties about cumulative CO_2 emissions compatible with this goal, in large part because of uncertainties about the role of non-CO_2 species, but it appears, based on past emissions and future projections, that the cumulative carbon threshold for this goal could be reached or exceeded in about two decades.

Key Finding 3

Achieving global greenhouse gas emissions reductions before 2030 consistent with targets and actions announced by governments in the lead up to the 2015 Paris climate conference would hold open the possibility of meeting the long-term temperature goal of limiting global warming to 3.6°F (2°C) above preindustrial levels, whereas there would be virtually no chance if global net emissions followed a pathway well above those implied by country announcements. Actions in the announcements are, by themselves, insufficient to meet a 3.6°F (2°C) goal; the likelihood of achieving that goal depends strongly on the magnitude of global emissions reductions after 2030. (*High confidence*)

Description of evidence base

The primary source supporting this key finding is Fawcett et al.;[27] it is also supported by Rogelj et al.,[24] Sanderson et al.,[25] and the Climate Action Tracker.[26] Each of these analyses evaluated the global climate implications of the aggregation of the individual country contributions thus far put forward under the Paris Agreement.

Major uncertainties

The largest uncertainty lies in the assumption of achieving emissions reductions consistent with the announcements prior to December 2015; these reductions are assumed to be achieved but could either be over- or underachieved. This in turn creates uncertainty about the extent of emissions reductions that would be needed after the first round of government announcements in order to achieve the 2°C or any other target. The response of the climate system, the climate sensitivity, is also a source of uncertainty; the Fawcett et al. analysis used the IPCC AR5 range, 1.5° to 4.5°C.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

There is *high* confidence in this key finding because a number of analyses have examined the implications of these announcements and have come to similar conclusions, as captured in this key finding.

Summary sentence or paragraph that integrates the above information

Different analyses have estimated the implications for global mean temperature of the emissions reductions consistent with the actions announced by governments in the lead up to the 2015 Paris climate conference and have reached similar conclusions. Assuming emissions reductions indicated in these announcements are achieved, along with a range of climate sensitivities, these contributions provide some likelihood of meeting the long-term goal of limiting global warming to well below 3.6°F (2°C) above preindustrial levels, but much depends on assumptions about what happens after 2030.

Key Finding 4

Further assessments of the technical feasibilities, costs, risks, co-benefits, and governance challenges of climate intervention or geoengineering strategies, which are as yet unproven at scale, are a necessary step before judgments about the benefits and risks of these approaches can be made with high confidence. (*High confidence*)

Description of evidence base

Key Finding 4 contains qualitative statements based on the growing literature addressing this topic, including from such bodies as the National Academy of Sciences and the Royal Society, coupled with judgment by the authors about the future interest level in this topic.

Major uncertainties

The major uncertainty is how public perception and interest among policymakers in climate intervention may change over time, even independently from the perceived level of progress made towards reducing CO_2 and other GHG emissions over time.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

There is *high* confidence that climate intervention strategies may gain greater attention, especially if efforts to slow the buildup of atmospheric CO_2 and other GHGs are considered inadequate by many in the scientific and policy communities.

Summary sentence or paragraph that integrates the above information

The key finding is a qualitative statement based on the growing literature on this topic. The uncertainty moving forward is the comfort level and desire among numerous stakeholders to research and potentially carry out these climate intervention strategies, particularly in light of how progress by the global community to reduce GHG emissions is perceived.

REFERENCES

1. Ciais, P., C. Sabine, G. Bala, L. Bopp, V. Brovkin, J. Canadell, A. Chhabra, R. DeFries, J. Galloway, M. Heimann, C. Jones, C. Le Quéré, R.B. Myneni, S. Piao, and P. Thornton, 2013: Carbon and other biogeochemical cycles. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 465–570. http://www.climatechange2013.org/report/full-report/

2. Joos, F., R. Roth, J.S. Fuglestvedt, G.P. Peters, I.G. Enting, W. von Bloh, V. Brovkin, E.J. Burke, M. Eby, N.R. Edwards, T. Friedrich, T.L. Frölicher, P.R. Halloran, P.B. Holden, C. Jones, T. Kleinen, F.T. Mackenzie, K. Matsumoto, M. Meinshausen, G.K. Plattner, A. Reisinger, J. Segschneider, G. Shaffer, M. Steinacher, K. Strassmann, K. Tanaka, A. Timmermann, and A.J. Weaver, 2013: Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: A multi-model analysis. *Atmospheric Chemistry and Physics,* **13**, 2793-2825. http://dx.doi.org/10.5194/acp-13-2793-2013

3. Collins, M., R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao, W.J. Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A.J. Weaver, and M. Wehner, 2013: Long-term climate change: Projections, commitments and irreversibility. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1029–1136. http://www.climatechange2013.org/report/full-report/

4. Solomon, S., G.K. Plattner, R. Knutti, and P. Friedlingstein, 2009: Irreversible climate change due to carbon dioxide emissions. *Proceedings of the National Academy of Sciences of the United States of America,* **106**, 1704-1709. http://dx.doi.org/10.1073/pnas.0812721106

5. Tebaldi, C. and P. Friedlingstein, 2013: Delayed detection of climate mitigation benefits due to climate inertia and variability. *Proceedings of the National Academy of Sciences,* **110**, 17229-17234. http://dx.doi.org/10.1073/pnas.1300005110

6. Prather, M.J., J.E. Penner, J.S. Fuglestvedt, A. Kurosawa, J.A. Lowe, N. Höhne, A.K. Jain, N. Andronova, L. Pinguelli, C. Pires de Campos, S.C.B. Raper, R.B. Skeie, P.A. Stott, J. van Aardenne, and F. Wagner, 2009: Tracking uncertainties in the causal chain from human activities to climate. *Geophysical Research Letters,* **36**, L05707. http://dx.doi.org/10.1029/2008GL036474

7. Kirtman, B., S.B. Power, J.A. Adedoyin, G.J. Boer, R. Bojariu, I. Camilloni, F.J. Doblas-Reyes, A.M. Fiore, M. Kimoto, G.A. Meehl, M. Prather, A. Sarr, C. Schär, R. Sutton, G.J. van Oldenborgh, G. Vecchi, and H.J. Wang, 2013: Near-term climate change: Projections and predictability. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, UK and New York, NY, USA, 953–1028. http://www.climatechange2013.org/report/full-report/

8. Paltsev, S., E. Monier, J. Scott, A. Sokolov, and J. Reilly, 2015: Integrated economic and climate projections for impact assessment. *Climatic Change,* **131**, 21-33. http://dx.doi.org/10.1007/s10584-013-0892-3

9. Tebaldi, C. and M.F. Wehner, 2016: Benefits of mitigation for future heat extremes under RCP4.5 compared to RCP8.5. *Climatic Change,* **First online**, 1-13. http://dx.doi.org/10.1007/s10584-016-1605-5

10. Zaelke, D. and N. Borgford-Parnell, 2015: The importance of phasing down hydrofluorocarbons and other short-lived climate pollutants. *Journal of Environmental Studies and Sciences,* **5**, 169-175. http://dx.doi.org/10.1007/s13412-014-0215-7

11. Myhre, G., D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, J.-F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura, and H. Zhang, 2013: Anthropogenic and natural radiative forcing. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 659–740. http://www.climatechange2013.org/report/full-report/

12. Bond, T.C., S.J. Doherty, D.W. Fahey, P.M. Forster, T. Berntsen, B.J. DeAngelo, M.G. Flanner, S. Ghan, B. Kärcher, D. Koch, S. Kinne, Y. Kondo, P.K. Quinn, M.C. Sarofim, M.G. Schultz, M. Schulz, C. Venkataraman, H. Zhang, S. Zhang, N. Bellouin, S.K. Guttikunda, P.K. Hopke, M.Z. Jacobson, J.W. Kaiser, Z. Klimont, U. Lohmann, J.P. Schwarz, D. Shindell, T. Storelvmo, S.G. Warren, and C.S. Zender, 2013: Bounding the role of black carbon in the climate system: A scientific assessment. *Journal of Geophysical Research Atmospheres,* **118**, 5380-5552. http://dx.doi.org/10.1002/jgrd.50171

13. Anenberg, S.C., J. Schwartz, D. Shindell, M. Amann, G. Faluvegi, Z. Klimont, G. Janssens-Maenhout, L. Pozzoli, R. Van Dingenen, E. Vignati, L. Emberson, N.Z. Muller, J.J. West, M. Williams, V. Demkine, W.K. Hicks, J. Kuylenstierna, F. Raes, and V. Ramanathan, 2012: Global air quality and health co-benefits of mitigating near-term climate change through methane and black carbon emission controls. *Environmental Health Perspectives*, **120**, 831-839. http://dx.doi.org/10.1289/ehp.1104301

14. Rao, S., Z. Klimont, J. Leitao, K. Riahi, R. van Dingenen, L.A. Reis, K. Calvin, F. Dentener, L. Drouet, S. Fujimori, M. Harmsen, G. Luderer, C. Heyes, J. Strefler, M. Tavoni, and D.P. van Vuuren, 2016: A multi-model assessment of the co-benefits of climate mitigation for global air quality. *Environmental Research Letters*, **11**, 124013. http://dx.doi.org/10.1088/1748-9326/11/12/124013

15. Hayhoe, K.A.S., H.S. Kheshgi, A.K. Jain, and D.J. Wuebbles, 1998: Tradeoffs in fossil fuel use: The effects of CO2, CH4, and SO2 aerosol emissions on climate. *World Resources Review,* **10**.

16. Shah, N., M. Wei, E.L. Virginie, and A.A. Phadke, 2015: Benefits of Leapfrogging to Superefficiency and Low Global Warming Potential Refrigerants in Room Air Conditioning. Lawrence Berkeley National Laboratory, Energy Technology Area, Berkeley, CA. 39 pp. https://eetd.lbl.gov/publications/benefits-of-leapfrogging-to-superef-0

17. Shindell, D., J.C.I. Kuylenstierna, E. Vignati, R. van Dingenen, M. Amann, Z. Klimont, S.C. Anenberg, N. Muller, G. Janssens-Maenhout, F. Raes, J. Schwartz, G. Faluvegi, L. Pozzoli, K. Kupiainen, L. Hoglund-Isaksson, L. Emberson, D. Streets, V. Ramanathan, K. Hicks, N.T.K. Oanh, G. Milly, M. Williams, V. Demkine, and D. Fowler, 2012: Simultaneously mitigating near-term climate change and improving human health and food security. *Science,* **335**, 183-189. http://dx.doi.org/10.1126/science.1210026

18. Rogelj, J., M. Meinshausen, M. Schaeffer, R. Knutti, and K. Riahi, 2015: Impact of short-lived non-CO_2 mitigation on carbon budgets for stabilizing global warming. *Environmental Research Letters,* **10**, 075001. http://dx.doi.org/10.1088/1748-9326/10/7/075001

19. NRC, 2011: *Climate Stabilization Targets: Emissions, Concentrations, and Impacts over Decades to Millennia*. National Research Council. The National Academies Press, Washington, D.C., 298 pp. http://dx.doi.org/10.17226/12877

20. Le Quéré, C., R.M. Andrew, J.G. Canadell, S. Sitch, J.I. Korsbakken, G.P. Peters, A.C. Manning, T.A. Boden, P.P. Tans, R.A. Houghton, R.F. Keeling, S. Alin, O.D. Andrews, P. Anthoni, L. Barbero, L. Bopp, F. Chevallier, L.P. Chini, P. Ciais, K. Currie, C. Delire, S.C. Doney, P. Friedlingstein, T. Gkritzalis, I. Harris, J. Hauck, V. Haverd, M. Hoppema, K. Klein Goldewijk, A.K. Jain, E. Kato, A. Körtzinger, P. Landschützer, N. Lefèvre, A. Lenton, S. Lienert, D. Lombardozzi, J.R. Melton, N. Metzl, F. Millero, P.M.S. Monteiro, D.R. Munro, J.E.M.S. Nabel, S.I. Nakaoka, K. O'Brien, A. Olsen, A.M. Omar, T. Ono, D. Pierrot, B. Poulter, C. Rödenbeck, J. Salisbury, U. Schuster, J. Schwinger, R. Séférian, I. Skjelvan, B.D. Stocker, A.J. Sutton, T. Takahashi, H. Tian, B. Tilbrook, I.T. van der Laan-Luijkx, G.R. van der Werf, N. Viovy, A.P. Walker, A.J. Wiltshire, and S. Zaehle, 2016: Global carbon budget 2016. *Earth System Science Data*, **8**, 605-649. http://dx.doi.org/10.5194/essd-8-605-2016

21. Allen, M.R., D.J. Frame, C. Huntingford, C.D. Jones, J.A. Lowe, M. Meinshausen, and N. Meinshausen, 2009: Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature*, **458**, 1163-1166. http://dx.doi.org/10.1038/nature08019

22. Nordhaus, W.D., 1975: Can We Control Carbon Dioxide? International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria. 47 pp. http://pure.iiasa.ac.at/365/

23. Stockholm Environment Institute, 1990: Targets and Indicators of Climatic Change. Rijsberman, F.R. and R.J. Swart (Eds.). Stockholm Environment Institute, Stockholm, Sweden. 166 pp. https://www.sei-international.org/mediamanager/documents/Publications/SEI-Report-TargetsAndIndicatorsOfClimaticChange-1990.pdf

24. Rogelj, J., M. den Elzen, N. Höhne, T. Fransen, H. Fekete, H. Winkler, R. Schaeffer, F. Sha, K. Riahi, and M. Meinshausen, 2016: Paris Agreement climate proposals need a boost to keep warming well below 2 °C. *Nature*, **534**, 631-639. http://dx.doi.org/10.1038/nature18307

25. Sanderson, B.M., B.C. O'Neill, and C. Tebaldi, 2016: What would it take to achieve the Paris temperature targets? *Geophysical Research Letters*, **43**, 7133-7142. http://dx.doi.org/10.1002/2016GL069563

26. Climate Action Tracker, 2016: Climate Action Tracker. http://climateactiontracker.org/global.html

27. Fawcett, A.A., G.C. Iyer, L.E. Clarke, J.A. Edmonds, N.E. Hultman, H.C. McJeon, J. Rogelj, R. Schuler, J. Alsalam, G.R. Asrar, J. Creason, M. Jeong, J. McFarland, A. Mundra, and W. Shi, 2015: Can Paris pledges avert severe climate change? *Science*, **350**, 1168-1169. http://dx.doi.org/10.1126/science.aad5761

28. UNFCCC, 2015: Paris Agreement. United Nations Framework Convention on Climate Change, [Bonn, Germany]. 25 pp. http://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf

29. NAS, 2015: *Climate Intervention: Carbon Dioxide Removal and Reliable Sequestration*. The National Academies Press, Washington, DC, 154 pp. http://dx.doi.org/10.17226/18805

30. NAS, 2015: *Climate Intervention: Reflecting Sunlight to Cool Earth*. The National Academies Press, Washington, DC, 260 pp. http://dx.doi.org/10.17226/18988

31. Fuss, S., J.G. Canadell, G.P. Peters, M. Tavoni, R.M. Andrew, P. Ciais, R.B. Jackson, C.D. Jones, F. Kraxner, N. Nakicenovic, C. Le Quere, M.R. Raupach, A. Sharifi, P. Smith, and Y. Yamagata, 2014: Betting on negative emissions. *Nature Climate Change*, **4**, 850-853. http://dx.doi.org/10.1038/nclimate2392

32. Smith, P., S.J. Davis, F. Creutzig, S. Fuss, J. Minx, B. Gabrielle, E. Kato, R.B. Jackson, A. Cowie, E. Kriegler, D.P. van Vuuren, J. Rogelj, P. Ciais, J. Milne, J.G. Canadell, D. McCollum, G. Peters, R. Andrew, V. Krey, G. Shrestha, P. Friedlingstein, T. Gasser, A. Grubler, W.K. Heidug, M. Jonas, C.D. Jones, F. Kraxner, E. Littleton, J. Lowe, J.R. Moreira, N. Nakicenovic, M. Obersteiner, A. Patwardhan, M. Rogner, E. Rubin, A. Sharifi, A. Torvanger, Y. Yamagata, J. Edmonds, and C. Yongsung, 2016: Biophysical and economic limits to negative CO2 emissions. *Nature Climate Change*, **6**, 42-50. http://dx.doi.org/10.1038/nclimate2870

33. Keith, D.W., R. Duren, and D.G. MacMartin, 2014: Field experiments on solar geoengineering: Report of a workshop exploring a representative research portfolio. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **372**, 20140175. http://dx.doi.org/10.1098/rsta.2014.0175

34. Kravitz, B., K. Caldeira, O. Boucher, A. Robock, P.J. Rasch, K. Alterskjær, D.B. Karam, J.N.S. Cole, C.L. Curry, J.M. Haywood, P.J. Irvine, D. Ji, A. Jones, J.E. Kristjánsson, D.J. Lunt, J.C. Moore, U. Niemeier, H. Schmidt, M. Schulz, B. Singh, S. Tilmes, S. Watanabe, S. Yang, and J.-H. Yoon, 2013: Climate model response from the Geoengineering Model Intercomparison Project (GeoMIP). *Journal of Geophysical Research Atmospheres*, **118**, 8320-8332. http://dx.doi.org/10.1002/jgrd.50646

35. Pierce, J.R., D.K. Weisenstein, P. Heckendorn, T. Peter, and D.W. Keith, 2010: Efficient formation of stratospheric aerosol for climate engineering by emission of condensible vapor from aircraft. *Geophysical Research Letters*, **37**, L18805. http://dx.doi.org/10.1029/2010GL043975

36. Tilmes, S., B.M. Sanderson, and B.C. O'Neill, 2016: Climate impacts of geoengineering in a delayed mitigation scenario. *Geophysical Research Letters*, **43**, 8222-8229. http://dx.doi.org/10.1002/2016GL070122

37. Keith, D.W. and D.G. MacMartin, 2015: A temporary, moderate and responsive scenario for solar geoengineering. *Nature Climate Change*, **5**, 201-206. http://dx.doi.org/10.1038/nclimate2493

38. Ricke, K.L., M.G. Morgan, and M.R. Allen, 2010: Regional climate response to solar-radiation management. *Nature Geoscience*, **3**, 537-541. http://dx.doi.org/10.1038/ngeo915

39. MacMartin, D.G., D.W. Keith, B. Kravitz, and K. Caldeira, 2013: Management of trade-offs in geoengineering through optimal choice of non-uniform radiative forcing. *Nature Climate Change*, **3**, 365-368. http://dx.doi.org/10.1038/nclimate1722

40. MacCracken, M.C., 2016: The rationale for accelerating regionally focused climate intervention research. *Earth's Future*, **4**, 649-657. http://dx.doi.org/10.1002/2016EF000450

41. Shepherd, J.G., K. Caldeira, P. Cox, J. Haigh, D. Keith, B. Launder, G. Mace, G. MacKerron, J. Pyle, S. Rayner, C. Redgwell, and A. Watson, 2009: *Geoengineering the Climate: Science, Governance and Uncertainty*. Royal Society, 82 pp. http://eprints.soton.ac.uk/156647/1/Geoengineering_the_climate.pdf

42. IPCC, 2013: Summary for policymakers. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley, Eds. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1–30. http://www.climatechange2013.org/report/