PERSPECTIVE

Well below 2 °C: Mitigation strategies for avoiding dangerous to catastrophic climate changes

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The historic Paris Agreement calls for limiting global temperature rise to "well below 2 °C." Because of uncertainties in emission scenarios, climate, and carbon cycle feedback, we interpret the Paris Agreement in terms of three climate risk categories and bring in considerations of low-probability (5%) high-impact (LPHI) warming in addition to the central (~50% probability) value. The current risk category of dangerous warming is extended to more categories, which are defined by us here as follows: >1.5 °C as dangerous; >3 °C as catastrophic; and >5 °C as unknown, implying beyond catastrophic, including existential threats. With unchecked emissions, the central warming can reach the dangerous level within three decades, with the LPHI warming becoming catastrophic by 2050. We outline a three-lever strategy to limit the central warming below the dangerous level and the LPHI below the catastrophic level, both in the near term (<2050) and in the long term (2100): the carbon neutral (CN) lever to achieve zero net emissions of CO_2, the super pollutant (SP) lever to mitigate short-lived climate pollutants, and the carbon extraction and sequestration (CES) lever to thin the atmospheric CO_2 blanket. Pulling on both CN and SP levers and bending the emissions curve by 2020 can keep the central warming below dangerous levels. To limit the LPHI warming below dangerous levels, the CES lever must be pulled as well to extract as much as 1 trillion tons of CO_2 before 2100 to both limit the preindustrial to 2100 cumulative net CO_2 emissions to 2.2 trillion tons and bend the warming curve to a cooling trend.

climate change | short-live climate pollutants | carbon capture | mitigation | air pollution

The Paris Agreement and its intended nationally determined contributions (INDCs) to reduce emissions (1) are unprecedented first steps for stabilizing global average warming to well below 2 °C (WB2C). It is generally acknowledged that the INDCs must be strengthened significantly to bend the climate emissions curve sufficiently and soon enough to limit the warming to WB2C (1–3). The overall objectives of this perspective piece are threefold:

i) Assess the low-probability (5%) high-impact (LPHI) warming outcomes in the absence of a climate mitigation policy after accounting for major uncertainties in: (*a*) future emission trajectories; (*b*) physical climate feedback involving water vapor, clouds, and snow/ice albedo; (*c*) carbon cycle feedback involving biogeochemistry; and (*d*) aerosol radiative forcing. We ensure that the extreme outcomes projected in this study are consistent with published model parameters. The warming estimates in this study account for the well-known greenhouse gases (GHGs) and various aerosols (Box 1).

ii) Identify the constraints imposed by WB2C and the criteria for meeting WB2C, and thus sharpen the definition of WB2C.

iii) Explore the mitigation pathways that are still available to meet the WB2C goal.

This perspective article weaves in science perspectives with societal perspectives since the two are inextricably linked. For example, the mitigation pathways we choose are largely motivated by the magnitude and rapidity of societal as well as ecosystem impacts (4) (Box 2). We recognize that the metrics for fully comprehending the societal impacts need to extend beyond global average warming (5), but global warming is still a valuable and accepted metric for strategizing mitigation options (6).

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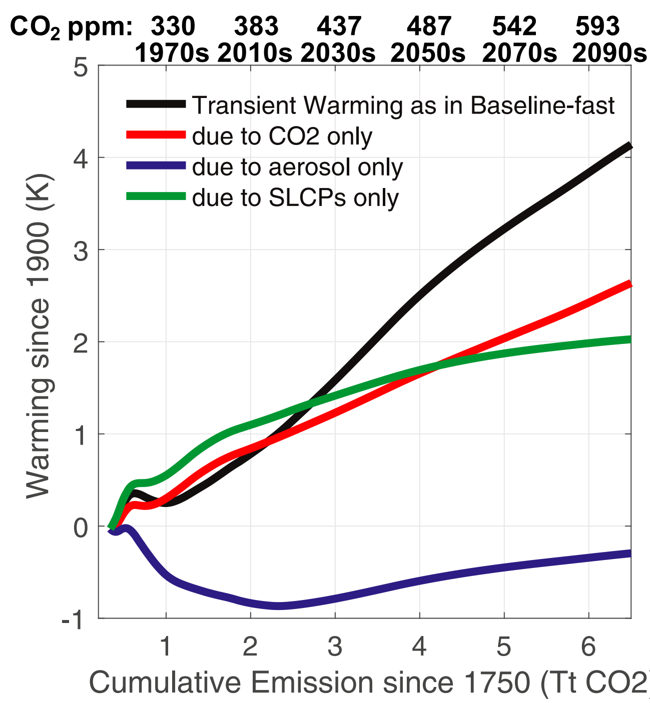
Box 1. The Non-CO_2 Climate Pollutants

The first category is SLCPs, which include GHGs such as methane, tropospheric ozone, HFCs, and aerosols such as BC, and coemitted OC. The lifetimes of these pollutants range from days (BC and OC), to months (tropospheric ozone), to about a decade (methane and HFCs), which explains the term "short-lived" in SLCPs. The second category of non-CO_2 climate pollutants includes LLGHGs such as N_2O and halocarbons other than HFCs (e.g., CFCs, HCFCs). Our model is forced by IPCC historical forcing of all non-CO_2 gases and aerosols. The third category of non-CO_2 climate pollutants is cooling aerosols (other than BC and OC) such as sulfates, nitrates, and dust. It should be noted that those cooling aerosols, along with the BC and OC aerosols included under SLCPs, are the major source of air pollution, leading to about 7 million deaths annually (31).

Box 1 Figure shows the individual contribution of CO_2, SLCPs, and cooling aerosols (other than those included in SLCPs) to the transient warming during the 20th and 21st centuries. All of the warming trends are relative to preindustrial temperatures. By 2015, the warming due to CO_2 is about 0.8 °C and that due to SLCPs is about 1.1 °C. The sum of the CO_2 and SLCP warming is already close to the Paris Agreement limit of 2 °C by 2015. On the other hand, the aerosols have a cooling ("masking") effect of about −0.9 °C. When we add the sum of the CO_2, SLCPs, and aerosol effects to the warming due to non-CO_2 LLGHGs, the estimated warming by 2015 is ∼1.1 °C (black curve in Box 1 Figure), which can be compared with the observed warming of about 1 °C (*SI Appendix*, Fig. S1). The main inference from Box 1 Figure is that CO_2 and SLCPs have exerted comparable warming effects (0.8 °C and 1.1 °C) to the past, while the aerosol masking effect is also comparable in magnitude but of opposite sign, with a cooling of −0.9 °C.



Box 1 Figure. Simulated transient warming (°C) following the baseline-fast scenario, as a function of the cumulative emission of CO_2 (*x* axis; black line). The decades at which each additional trillion tons of CO_2 was emitted and the corresponding CO_2 concentration are shown at the top. The red, blue, and green lines illustrate transient simulated warming due to CO_2, cooling aerosols, and SLCPs only, respectively.

Projected Warming in the Absence of Climate Policies

A convenient place to start the discussion is the projected warming in the absence of climate policies. Determining this baseline warming sets the stage for exploring and justifying mitigation pathways. Published future CO_2 emission scenarios (1, 4), along with historical emissions, are fed into a carbon cycle model to estimate the CO_2 concentration during the 20th and 21st centuries (*SI Appendix*, Figs. S1 and S2). The calculated CO_2 concentration is used to estimate its climate forcing (*SI Appendix*, Figs. S4 and S6). For climate forcing due to other atmospheric compositions, we adopted the Intergovernmental Panel on Climate Change (IPCC)-derived historical values (Box 1) and future projections (*SI Appendix*, Fig. S6). The temperature response is estimated with an energy balance climate model (*SI Appendix*, section 1). In a series of published studies (7–10), the carbon cycle model and the climate model simulations have been extensively validated by comparison with observations of atmospheric CO_2 (7) (*SI Appendix*, Figs. S1 and S2), global mean temperature (8), ocean heat content (box 1 of ref. 7), and sea-level rise (figure 2 of ref. 9), as well as by comparison with published projections from 3D global climate model simulations (9, 10).

The projected warming (relative to 1900) at 2050 and 2100 is shown in Fig. 1, under the two baseline emission scenarios in the absence of climate policy during the 21st century. The temporal evolution of CO_2 emissions, CO_2 concentrations, and global average temperatures are shown in *SI Appendix*, Fig. S1. To generate the probability distribution curves shown in Fig. 1 (as well as in *SI Appendix*, Figs. S3, S9, and S10), temperature under each scenario is simulated with 1,500 stochastic runs to cover the full range of climate sensitivity involving feedback related to water vapor, clouds,

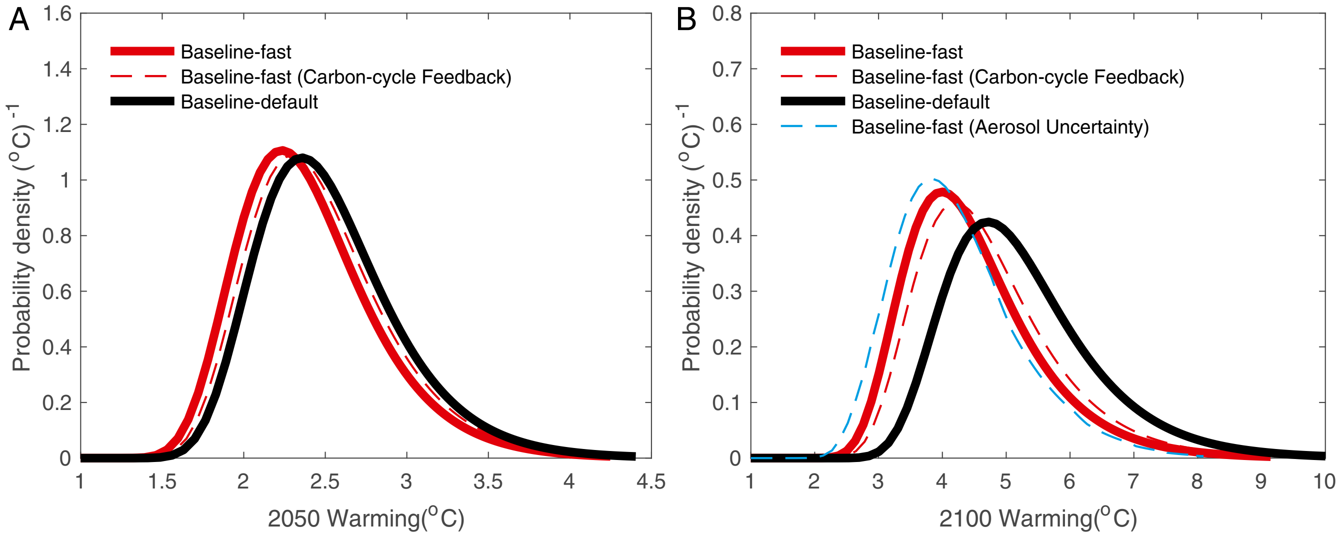


Fig. 1. Probability density function of projected warming for 2050 (*A*) and 2100 (*B*) for the baseline-fast (thick red line) and baseline-default (thick black line) scenarios. The base year for the warming estimates is 1900. The red dashed line shows the projection forced by the baseline-fast CO_2 emission, but a positive carbon cycle feedback due to the ocean and land carbon uptake reduction is included. The blue dashed line in *B* shows the projection in which the aerosol forcing uncertainty is considered as well.

and snow/ice albedo (*SI Appendix*, section 1), hereafter referred to as climate physical-dynamical feedback. The projected warming is shown for two baseline emission scenarios proposed by the IPCC (4): baseline-fast and baseline-default. The baseline-fast scenario assumes an aggressive 80% reduction in the energy intensity of the economy (still using fossil fuels) compared with the 2010 energy intensity. The baseline-default scenario adopts the current rate of reduction in energy intensity until 2100, achieving a 50% reduction from the 2010 level. The two baseline emission trajectories, along with the corresponding 5–95% range within each scenario (shading in *SI Appendix*, Fig. S1), capture expert projections for a plausible range of future emissions in the absence of climate policies.

In what follows, the analyses rely mainly on the central (50%) and LPHI (upper 5%) values of the probability distribution shown in Fig. 1 and elsewhere. So, we first comment on how the present model compares with published studies on the central and upper 5% probability climate sensitivities. The central (50%) value of equilibrium climate sensitivity adopted in our model is 3 °C for a doubling of CO_2 and is consistent with the published 30-model mean value of 3.2 °C in the most recent IPCC report (11). The transient climate response of this model to a gradual increase in CO_2 is also within 10% of the IPCC 30-model mean values (more elaboration on the validation of the climate sensitivity is provided in *SI Appendix*, section 3). The 5% probability values (Fig. 2 and *SI Appendix*, Figs. S9 and S10) are about 45–50% higher than the central value, and these are also consistent with published values for the 95% percentile of climate model values. For example, among the 30 models assessed in the IPCC report, the central value of climate sensitivity is 3.2 °C, while two of the 30 models yield a sensitivity of 4.5 °C and 4.7 °C (about 40–46% higher than the central value).

The primary inference from Fig. 1 and *SI Appendix*, Fig. S1 is the following: There is a 50% probability of 2.4 (baseline-fast)–2.6 °C (baseline-default) warming in the near term (2050) and 4.1–5 °C warming by 2100. For the rest of this discussion, the lower value represents the baseline-fast scenario and the upper value represents the baseline-default scenario. In evaluating the 50% probability, we assumed both baseline scenarios are equally probable as there is no prior basis for choosing one over the other. The warming range of 4.1–5 °C at 2100 (since 1900) compares favorably with the published estimates of 4.9 °C warming (12) and 3.7 °C for the periods between 1986–2005 and 2081–2100 (13). Since this study attempts to evaluate the extreme outcomes consistent with data and published model parameters, we also examine the LPHI (5% probability) values. The LPHI warming under the two baseline scenarios can exceed 3.5–4 °C by 2050 and 6.5–8 °C by 2100 (Fig. 1). Note that the 5–95% range in the projected warming due to emission uncertainties within each baseline scenario is less than 0.3 °C for 2050 and ∼0.7–1 °C for 2100 (red shading in *SI Appendix*, Fig. S1).

The warming probability distribution shown in Fig. 1 (and elsewhere in this paper) is due to the wide range of uncertainties in modeling the climate feedbacks (14). The upper range of warming projection, with a probability of less than 5% (Figs. 1 and 2), may appear unrealistically large, but this may not be the case. Here, we choose to use a high range of climate sensitivity because some studies have suggested that 3D climate models have underestimated three major positive climate feedbacks: positive ice albedo feedback from the retreat of Arctic sea ice (15), positive cloud albedo feedback from retreating storm track clouds in mid-latitudes (16, 17), and positive albedo feedback by the mixed-phase

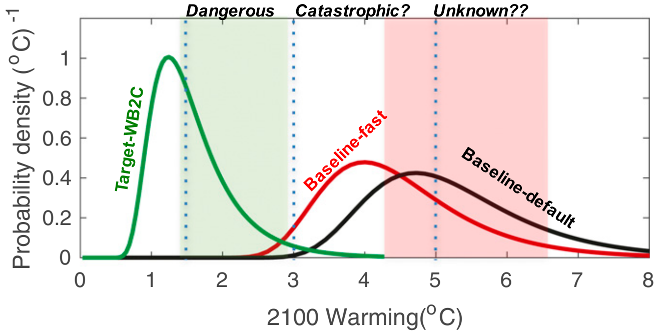


Fig. 2. Probability density function of projected warming in 2100 for the baseline-default, baseline-fast, and Target-WB2C (CN2030 + SLCP2020 + CES1t) scenarios. The green and red color shading shows the 50–95% range of the projection for the Target-WB2C and baseline-fast scenarios due to uncertainty in climate sensitivity. The vertical dotted lines indicate the range of the three risk categories as defined in this study.

(water and ice) clouds (18) (more discussion is provided in SI Appendix, section 5). The potential underestimation of these feedbacks, along with the positive carbon cycle feedback to be described below, persuaded us to show the warming distribution (Figs. 1 and 2 and SI Appendix) for low probabilities much less than 5%. Again, we caution that we do not use the projected warming with a probability less than 5% for rest of the mitigation analyses.

Thus far, the thick curves in Fig. 1 and SI Appendix, Fig. S1 capture the uncertainties in the emissions scenarios and in the model treatment of climate physical-dynamical feedback. There are two other major sources of uncertainties:

i) Aerosol radiative forcing uncertainties and their entanglement with climate sensitivity estimate (19). These uncertainties, when included in the probability distribution shown in Fig. 1*B* (blue dashed line), would slightly change the skewed distribution of the projected warming.

ii) Biogeochemical feedback between climate change and the carbon cycle. Different climate-carbon feedbacks, all of which amplify the warming, are considered below. The first feedback deals with the decrease in the oceanic and land uptake of carbon with warming, the second is the release of soil carbon due to the thawing of the permafrost, and the third is the increase in carbon emission (as CO_2 and methane) from wetlands (20). Recent studies using 3D climate models coupled with a biogeochemistry component have systemically examined the carbon cycle response to future warming (21), which revealed the following: Modeling uncertainties introduce a −16% to 13% uncertainty range in the cumulative emission (as of 2100), climate-carbon feedback on the carbon uptake by land and oceans introduces a 6–27% increase in the cumulative emissions from 2010 to 2100, and the permafrost thawing can release soil carbon and increase cumulative emission by 3–13% from 2010 to 2100. Introducing the central value of the three processes above (21) effectively increases the baseline-fast carbon emissions by ∼20% and can enhance warming by less than 0.5 °C (red dashed lines in Fig. 1). Also, the warming has been projected to increase methane emissions from wetlands by 0–100% compared with present-day wetland methane emissions. A 50% increase in wetland methane emissions by 2100 in response to the 4.1–5 °C warming could add at least another 0.5 °C (50% probability) to the projected warming.

In summary, the aerosol forcing uncertainty, although large in the 20th century, had only a small impact (<0.2 °C) on the projected warming trends (Fig. 1*B*). The climate-carbon feedback can amplify warming by ∼0.5–1 °C. This amplification, albeit large, was not included in our discussion on LPHI (5% probability) projections, because although the CO_2 emissions from permafrost thawing and methane emissions from warmer wetlands are certain to increase, there is little confidence in the magnitude of the increase. A more detailed discussion of the major uncertainties mentioned above and the skewed probability distribution due to climate sensitivity is given in the SI Appendix, sections 4 and 5. It should also be pointed out that the probabilistic approach for projecting climate has been recognized and adopted in earlier studies (22–25), and its application in assigning climate risk is an active area of research (Box 2).

Constraints and Criteria

Based on analyses of available studies and model projections presented here, we propose the following constraints and criteria as governing principles for mitigation strategies.

Assigning Climate Risks. Following the societal risk characterization as defined in Box 2, the projected warming trends in Fig. 1 for the two scenarios without climate policies fall under the following risk categories.

Near term (<2050). Within three decades, the warming has a 50% probability of reaching dangerous levels (>1.5 °C), with the LPHI warming reaching catastrophic levels (>3 °C).

Long term (>2050). Within eight decades, the warming has a 50% probability of subjecting the global population to catastrophic (>3 °C) to unknown risks (>5 °C) and a 5% probability of being fully in the unknown risk category, which also includes existential threats for everyone.

Mitigation Criteria for Warming. The meaning of the phrase "well below 2 °C" was not adequately defined in the Paris Agreement. A hint was given through the aspirational goal of limiting the warming to "below 1.5 °C." Using the probability approach, we propose that mitigation measures attempting to limit the warming to WB2C must consider adopting the following criteria: (*i*) The warming should be limited to below dangerous levels with at least a 50% probability; (*ii*) in addition, the LPHI warming should be limited to below catastrophic levels; and (*iii*) instead of stabilizing at 1.5 °C or 2 °C, the warming must begin to decrease with time before the end of the 21st century. In other words, we must bend the warming curve by the end of the century. Why is this criterion for bending the warming curve important? The Eemian period of 130,000 years ago was an interglacial period similar to the present and was warmer by ∼1 °C. It was associated with a 6- to 9-m rise in sea level (26), which suggests that a warming of 1.5 °C or more sustained over centuries can cause a catastrophic sea level rise.

Time Constraints. The near-term (<2050) risk of dangerous (50% probability) to catastrophic imposes severe constraints on the urgency of the mitigation measures. Bending of the emission curves must begin now. As shown in earlier studies (27), future emissions largely determine the future warming for CO_2. The future net emission of CO_2 must be brought to zero before the warming exceeds dangerous levels. If the CO_2 emission is abruptly brought to zero by 2020, the CO_2 concentration will decrease soon after and the warming (due solely to CO_2) will stabilize at 2020 levels or even decrease slightly (SI Appendix, Fig. S8 *D–F*).

Because of the inertia in the socioeconomic system, the emissions most likely cannot be brought to zero immediately. Even if a scalable renewable technology were invented today to zero out all of the CO_2 emissions, it would be likely to take between three and five decades to spread such technology to the whole world (28), assuming a globally binding policy for carbon neutrality had already been put into place. This delay is partly due to the locked-in infrastructure and the upfront capital cost of quickly replacing as opposed to distributing the cost over decades. This inference is also consistent with most scenario studies (29, 30) for carbon neutrality pathways. The opposite extreme of zeroing out CO_2 emissions by 2020 is a more gradual reduction to near-zero emissions by 2100. For this case, SI Appendix, Fig. S8*B* shows simulated CO_2 concentrations increase by ∼20 ppm to peak levels by 2030 and stay flat post-2050 and CO_2-induced warming increases by another 0.6 °C (SI Appendix, Fig. S8*C*).

The constraint posed by the near-term (next three decades) risk of dangerous (50% probability) to catastrophic (5% probability) warming is that emission of CO_2 and short-lived climate pollutants (SLCPs) should peak immediately and bend downward by 2020. There are hopeful signs that this is not an unrealistic goal. Worldwide CO_2 emissions grew at a rate of 2.9% per year from 2000 to 2011, slowed to 1.3% per year from 2012 to 2014, and

Box 2. Risk Categorization of Climate Change to Society

The United Nations Framework Convention on Climate Change coined the phrase "dangerous anthropogenic interference" (DAI) with the climate system. The DAI phrase spurred quite a bit of research on what climate change means for society and the ecosystem (45). Subsequently, in 2001, the IPCC (46) came up with the burning embers diagram, in which it categorized climate risks under five reasons for concern (RFCs) that ranged from risks to natural systems, risks of extreme weather events, distribution of impacts between regions of the world, aggregate impacts, and risks of large-scale discontinuities. In the burning embers diagram, risks under each RFC were ranked based on the warming magnitude. For what follows, we adopt the most recent version of DAI analysis (47). At 2 °C, risks for two RFCs were designated as high, while at 4 °C, all RFCs were ranked as a high-risk category, with two of them ranked as very high. The burning embers diagram does not extend beyond 5 °C.

We are proposing the following extension to the DAI risk categorization: warming greater than 1.5 °C as "dangerous"; warming greater than 3 °C as "catastrophic?"; and warming in excess of 5 °C as "unknown??," with the understanding that changes of this magnitude, not experienced in the last 20+ million years, pose existential threats to a majority of the population. The question mark denotes the subjective nature of our deduction and the fact that catastrophe can strike at even lower warming levels. The justifications for the proposed extension to risk categorization are given below.

From the IPCC burning embers diagram and from the language of the Paris Agreement, we infer that the DAI begins at warming greater than 1.5 °C. Our criteria for extending the risk category beyond DAI include the potential risks of climate change to the physical climate system, the ecosystem, human health, and species extinction. Let us first consider the category of catastrophic (3 to 5 °C warming). The first major concern is the issue of tipping points. Several studies (48, 49) have concluded that 3 to 5 °C global warming is likely to be the threshold for tipping points such as the collapse of the western Antarctic ice sheet, shutdown of deep water circulation in the North Atlantic, dieback of Amazon rainforests as well as boreal forests, and collapse of the West African monsoon, among others. While natural scientists refer to these as abrupt and irreversible climate changes, economists refer to them as catastrophic events (49).

Warming of such magnitudes also has catastrophic human health effects. Many recent studies (50, 51) have focused on the direct influence of extreme events such as heat waves on public health by evaluating exposure to heat stress and hyperthermia. It has been estimated that the likelihood of extreme events (defined as 3-sigma events), including heat waves, has increased 10-fold in the recent decades (52). Human beings are extremely sensitive to heat stress. For example, the 2013 European heat wave led to about 70,000 premature mortalities (53). The major finding of a recent study (51) is that, currently, about 13.6% of land area with a population of 30.6% is exposed to deadly heat. The authors of that study defined deadly heat as exceeding a threshold of temperature as well as humidity. The thresholds were determined from numerous heat wave events and data for mortalities attributed to heat waves. According to this study, a 2 °C warming would double the land area subject to deadly heat and expose 48% of the population. A 4 °C warming by 2100 would subject 47% of the land area and almost 74% of the world population to deadly heat, which could pose existential risks to humans and mammals alike unless massive adaptation measures are implemented, such as providing air conditioning to the entire population or a massive relocation of most of the population to safer climates.

Climate risks can vary markedly depending on the socioeconomic status and culture of the population, and so we must take up the question of "dangerous to whom?" (54). Our discussion in this study is focused more on people and not on the ecosystem, and even with this limited scope, there are multitudes of categories of people. We will focus on the poorest 3 billion people living mostly in tropical rural areas, who are still relying on 18th-century technologies for meeting basic needs such as cooking and heating. Their contribution to CO_2 pollution is roughly 5% compared with the 50% contribution by the wealthiest 1 billion (55). This bottom 3 billion population comprises mostly subsistent farmers, whose livelihood will be severely impacted, if not destroyed, with a one- to five-year megadrought, heat waves, or heavy floods; for those among the bottom 3 billion of the world's population who are living in coastal areas, a 1- to 2-m rise in sea level (likely with a warming in excess of 3 °C) poses existential threat if they do not relocate or migrate. It has been estimated that several hundred million people would be subject to famine with warming in excess of 4 °C (54). However, there has essentially been no discussion on warming beyond 5 °C.

Climate change-induced species extinction is one major concern with warming of such large magnitudes (>5 °C). The current rate of loss of species is ~1,000-fold the historical rate, due largely to habitat destruction. At this rate, about 25% of species are in danger of extinction in the coming decades (56). Global warming of 6 °C or more (accompanied by increase in ocean acidity due to increased CO_2) can act as a major force multiplier and expose as much as 90% of species to the dangers of extinction (57).

The bodily harms combined with climate change-forced species destruction, biodiversity loss, and threats to water and food security, as summarized recently (58), motivated us to categorize warming beyond 5 °C as unknown??, implying the possibility of existential threats. Fig. 2 displays these three risk categorizations (vertical dashed lines).

further decreased to near-zero growth (−0.2% per year) for 2015. This near-zero growth rate continued into 2016 (2). The low to near-zero growth rate since 2014 is due to a combination of several factors: switching from coal to oil and natural gas; an increase in production of renewable energy such as nuclear (1.3%), hydro (1%), and wind and solar (15%); and a reduction in carbon intensity of the economy. The negative growth rate from the United States (−2.6%) and China (−0.7%) mostly contributed to the recent bending of the emissions curve. While these are encouraging signs, aggressive policies will still be required to achieve carbon neutrality and climate stability.

The other long-lived GHG (LLGHG) with nonnegligible forcing is nitrous oxide (N_2O) (*SI Appendix*, Fig. S6). Its current forcing is ~0.15 watts per square meter (Wm^{-2}) and is projected to increase to 0.23 Wm^{-2} by 2100 (*SI Appendix*, Fig. S6). Its net contribution to the warming from 2010 to 2100 is only about 0.1 °C (50% probability). Given the small size of its warming from the present to 2100 and the fact that N_2O emission is tied to agriculture and it is the greatest challenge in limiting N_2O emissions by 2100 with a world population of 10 billion, we are not targeting N_2O in the mitigation measures discussed here.

Super Pollutants (SLCPs). As of now, the CO_2 warming in conjunction with the larger than 1 °C future warming imposed by SLCPs (Box 1 Figure) makes it extremely difficult, if not impossible, to limit the near-term (next three decades) warming below the dangerous levels by reducing CO_2 concentrations. The following discussion is restricted to the impact of reducing the atmospheric concentrations of SLCPs with the required measures discussed later. This distinction is important since measures to reduce CO_2 would also indirectly reduce some of the SLCP emissions.

The four SLCPs [methane, tropospheric ozone, black carbon (BC), and hydrofluorocarbons (HFCs)] are referred to as super pollutants (SPs) since their global warming potential (on a 100-year time scale) ranges from 25 to 2,000. When the warming due to CO_2 is added to the SP warming, the 2 °C threshold should have been crossed, but for the masking effect of the −0.9 °C (−0.5 to −1.5 °C) aerosol cooling due to sulfate, nitrate, and dust aerosols (Box 1 Figure). Since these cooling aerosols [along with BC and organic carbon (OC) aerosols] are also the major sources of air pollution, leading up to 7 million mortalities (31), they are being regulated independent of climate mitigation regulations. Phasing out the cooling aerosols completely within a few decades (e.g., by switching to renewable fuels) can lead to an additional warming of about 0.3 °C between 2020 and 2050 (*SI Appendix*, Fig. S7).

In summary, dangerous to catastrophic climate changes in the near term can be avoided only by reducing the concentrations of SPs substantially beginning in 2020. Technological measures to reduce SLCPs are mostly available and fall under two categories:

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

ii) SLCP-dedicated measures. Technological measures independent of CO_2-dedicated measures are already available (34) for reducing methane, ozone, and BC concentration, and deploying immediately to scale is feasible. For the halocarbons, including HFCs, the Kigali amendment to the Montreal Protocol, which was approved by 160 nations (35), will phase out high-GWP (global warming potential) HFCs by 2050. The Montreal Protocol was unanimously adopted by the United Nations in the 1980s to ban chlorofluorocarbons (CFCs) due to the negative impact on the ozone layer, but it was also effective in mitigating the super greenhouse effect of these halocarbons (36). The Kigali amendment specifically recognized the climate-warming effect of halocarbons and approved phasing down these powerful climate pollutants.

The mitigation of the coemitted SLCPs and cooling aerosols by CO_2-dedicated measures requires special consideration (33). SLCP emissions are not entirely independent of CO_2 emissions, and emission rates of SLCPs can decrease due to CO_2 mitigation, and likewise CO_2 emissions can decrease due to mitigation of SLCPs. The role of coemitted SLCPs that are dependent on CO_2 is estimated in *SI Appendix*, Fig. S5. A fraction of CH_4 (about 70%) and BC (about 30%) emissions can be mitigated through CO_2-dedicated measures. While HFCs are not dependent on CO_2 mitigation, CO_2-dedicated mitigation measures can accomplish roughly 50% of the 0.6 °C mitigated warming by SLCPs by 2050 and 40% of the 1.2 °C mitigated warming by 2100. Another complexity of the coemission issue is that a major part of the cooling aerosols (mostly sulfates and nitrates) is also coemitted by CO_2-dedicated measures. Hence, the CO_2 measures implemented in 2020 will unmask some of the aerosol cooling (red lines in *SI Appendix*, Fig. S5) and offset the warming reduction by CO_2 and SLCP mitigation. In the baseline scenarios of this study, the cooling aerosols are regulated gradually between 2020 and 2100 (*SI Appendix*, Fig. S6), whereas in the mitigation scenario examined here, CO_2 mitigation is implemented starting from 2020 and CO_2 emission is brought to net zero in about three decades (*SI Appendix*, Fig. S2*B*). As a result, the unmasking of coemitted aerosol cooling (a net warming effect) is more rapid in the decreasing CO_2 emissions beginning in 2020 (CN2020) mitigation scenario (*SI Appendix*, Fig. S5*B* vs. S7).

Given the uncertainties in aerosol forcing; the socioeconomic and political challenges involved in CO_2 mitigation; climate feedback uncertainties; and, above all, the possibilities of catastrophic climate change (a 5% probability) within three decades, a no-regret policy will be to undertake both CO_2-dedicated and SLCP-dedicated measures simultaneously. In 2016, California did exactly that by passing the SB-1383 bill (37), which targets mitigation of methane, HFCs, and BC beginning in 2020. Since California has already passed laws to reduce CO_2 emissions by 80% before 2050, the SB-1383 bill is a demonstration that both CO_2 and the SPs can be mitigated simultaneously using complementary technologies. Furthermore, in 2011, the United Nations Environment Program formed the Climate and Clean Air Coalition (www.ccacoalition.org/en) to mitigate all four SLCPs in coalition with many member nations.

Mitigation: A Three-Lever Strategy

We will now take up the mitigation strategy subject to the criteria and constraints identified above. We have to consider two time scales. First is the near term of three decades extending from now to midcentury, when the warming is likely to cross over to the dangerous

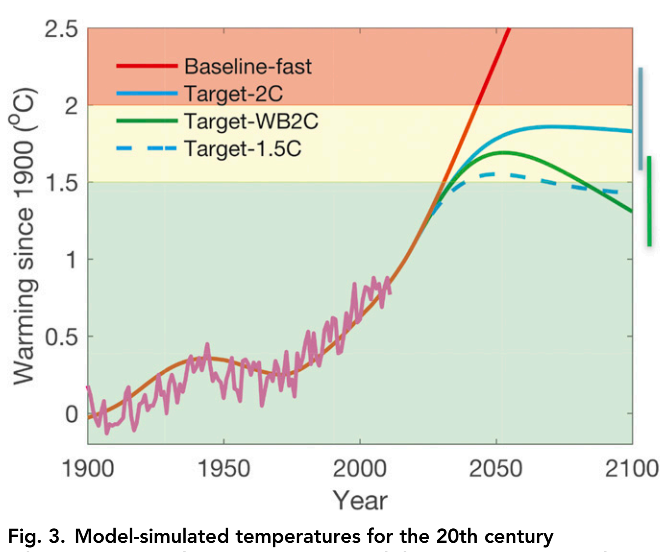


Fig. 3. Model-simulated temperatures for the 20th century (observations are shown in magenta) and their projections into the 21st century under four different scenarios: baseline-fast (red line); Target-2C (CN2030 + SLCP2020) with CO_2 mitigation starting at 2030 (CN2030), followed by decarbonization as in INDCs (blue solid line) [SLCPs are also mitigated starting from 2020 (SLCP2020)]; Target-WB2C (CN2030 + SLCP2020 + CES1t), which is the same as the blue solid line but also includes extraction of 1 trillion tons of CO_2 starting from 2030 (green solid line); and Target-1.5C, which is the same as the blue solid line, except that decarbonization starts earlier at 2020 (CN2020 + SLCP2020) (blue dashed line). The vertical bars on the right show the uncertainty of projected warming at 2100 due to climate sensitivity uncertainty (10–90%) for the cases of Target-2C (CN2030 + SLCP2020, blue solid line) and Target-WB2C (CN2030 + SLCP2020 + CES1t, green solid line).

threshold (baseline curves in Fig. 1*A* and Fig. 3). Next is the long term, extending from midcentury to 2100, when the baseline LPHI warming can reach beyond the catastrophic regime into the unknown domain (baseline curves in Fig. 1*B* and Fig. 2).

There are three levers available for bending the warming curve.

Carbon Neutral Lever. The carbon neutral (CN) lever is for mitigation of CO_2 emissions. It has taken society nearly 220 years (from 1750 to 1970) to emit the first trillion tons of CO_2 and only another 40 years (1970–2010) to emit the next trillion tons. The third trillion tons, under current emission trends, would be emitted by 2030 and the fourth trillion tons before 2050 (Box 1 and *SI Appendix*, Fig. S1*A*). Even if the INDCs are implemented rigorously and verifiably, the third trillion tons will be added by 2035 (*SI Appendix*, Fig. S2*A*). Earlier studies (30) have identified that cumulative CO_2 emissions must be limited to less than 3.7 trillion tons (or 1 trillion tons of carbon) to have any chance of limiting the warming below 2 °C. These studies often focused on targeting the central value (50% probability) of the warming and less on the LPHI warming. The maximum warming reduction feasible by pulling on the CN lever can be inferred from Box 1, which shows the 2100 baseline-fast warming by CO_2 alone to be 2.6 °C. Since the lifetime of CO_2 ranges from decades (for the first 50%), to centuries, to millennia (for 20%) (38), not all of the 2.6 °C warming can be mitigated by 2100. Constrained by CO_2 lifetime and the diffusion time of new technologies (decades), the scenarios considered here (*SI Appendix*, Fig. S2*A*) suggest that about half of the 2.6 °C CO_2 warming in the baseline-fast scenario can be mitigated by 2100 and only 0.1–0.3 °C can be mitigated by 2050.

Had we followed the baseline-default trajectory, the CO_2-alone warming would have been 3.5 °C instead of 2.6 °C as shown in Fig. 2. It is important to note both scenarios use fossil fuels. Since the baseline-default scenario reduces carbon intensity of the economy by only 50% from the 2010 values compared with an 80% reduction in the baseline-fast scenario, we infer that reducing the carbon intensity of the economy is a very potent mitigation measure since, by itself, it can reduce the 2100 CO_2 warming by 0.9 °C from 3.5 to 2.6 °C (additional details are provided in *SI Appendix*, section 6).

SP Lever. The SP lever targets SLCPs. Reducing SLCP emissions thins the SP blanket within few decades, given the shorter lifetimes of SLCPs (weeks for BC to about 15 years for HFCs). The mitigation potential of the SP lever with a maximum deployment of current technologies (32) is about 0.6 °C by 2050 and 1.2 °C by 2100 (*SI Appendix*, Fig. S5*B* and Table S1).

Carbon Extraction and Sequestration Lever. The third lever is the carbon extraction and sequestration (CES) lever, which will extract CO_2 from the source (e.g., the coal power plant) or from the air and sequester it. While the CN and SP levers can help mitigate the 50% probability warming targets, they are inadequate to mitigate the LPHI warming. Ultimately, we must thin the CO_2 greenhouse blanket by removing the CO_2 that is already in the atmosphere.

Given the near-term risk of exceeding the dangerous to catastrophic thresholds, the timing for pulling these levers is a crucial issue. Ideally, these levers should be pulled immediately by 2020. We will now elaborate on three options to constrain the choices considered in earlier studies, starting with the least preferable option first.

Target-2C option. This option involves following the INDCs until 2030 and bending the CO_2 emissions downward by 2030, and bending the SP (SLCP) emissions downward by 2020 and reaching full potential by 2060. The CO_2 part of this option is referred to as CN2030, while the SLCP part is referred to as SLCP2020 (Table 1). CN2030 will achieve carbon neutrality by 2060–2070, which will limit the cumulative CO_2 emissions (since preindustrial) to 3.2 trillion tons (*SI Appendix*, Fig. S2*A*). We refer to this as the Target-2C option since it has been proposed by several earlier studies (3, 23). However, even when CN2030 is combined with SLCP2020, the Target-2C option will only be able to limit the 50% probability warming below 2 °C (Fig. 3) but will fail to meet the mitigation criteria of avoiding dangerous warming (50% probability of warming less than 1.5 °C) both in the near term and in the long term (*SI Appendix*, Figs. S9 and S10).

Target-1.5C option. Instead of allowing CO_2 emissions to increase until 2030, we should start bending the curve by 2020 [i.e., CN2020 and achieving a CN status by 2050 (*SI Appendix*, Fig. S2*B*)]. Since 2020 is just a few years away, this is a highly optimistic option. The 10-year head start in bending the CO_2 curve, when combined with SLCP2020, was sufficient to bring down the probability of 1.5 °C warming (the threshold for dangerous warming) from more than 99% to less than 50% (blue dashed curve in *SI Appendix*, Figs. S9 and S10). Furthermore, advancing the CN lever by 10 years has reduced the probability of catastrophic warming (>3 °C) to below 5%. The main reason is because the CN2030 case allows additional emissions of 1.2 trillion

Table 1. Scenarios of CO_2 and SLCPs considered in the study

Scenario acronyms	Decarbonization pathway toward carbon neutrality starting at?	SLCPs mitigation starting at?	CES included?
Baseline-default (RCP8.5)	No (*SI Appendix*, Fig. S1*B*)	No	No
Baseline-fast (RCP6.0-like)	No (*SI Appendix*, Fig. S1*A*)	No	No
Target-2C (CN2030 + SLCP2020)	2030 (*SI Appendix*, Fig. S2*A*)	2020 (*SI Appendix*, Fig. S4)	No
Target-1.5C (CN2020 + SLCP2020)	2020 (*SI Appendix*, Fig. S2*B*)	2020 (*SI Appendix*, Fig. S4)	No
Target-WB2C (CN2030 + SLCP2020 + CES1t)	2030 (*SI Appendix*, Fig. S2*A*)	2020 (*SI Appendix*, Fig. S4)	Yes (*SI Appendix*, Fig. S2*C*)
FixedConcentration2020	2020, but the reduction rate is slower than CN2020 (*SI Appendix*, Fig. S8*A*)	No	No
ZeroEmission2020	2020, but the CO_2 emission is reduced to zero abruptly (*SI Appendix*, Fig. S8*B*)	No	No
CN2020 + SLCP2020-dependent	2020 (*SI Appendix*, Fig. S2*B*)	2020, but only includes the portion that is coemitted by CO_2 sources (*SI Appendix*, Fig. S5)	No

tons between 2010 and 2050 (*SI Appendix*, Fig. S2*A*), whereas in the CN2020 case, the additional increase is only 0.5 trillion tons (*SI Appendix*, Fig. S2*B*). The inference is that to meet the criteria for avoiding dangerous warming (<1.5 °C warming with 50% probability) as well as catastrophic warming (<3 °C warming with 95% probability), the cumulative emissions from preindustrial to 2100 must be less than 2.5 trillion tons of CO_2. This option, compared with the Target-2C option, illustrates the large impact of a 10-year delay in bending the CO_2 emissions curve on increasing the risks of climate change.

Target-WB2C option. This case involves pulling all three levers (CN, SP, and CES levers) with the CN2030 and the SLCP2020 options. This case is shown in Figs. 2 and 3 (green curves in both). The model simulations suggest that CES needs to be deployed by 2030 and to sequester 16 billion tons (Gt) of CO_2 per year (*SI Appendix*, Fig. S2*C*) for several decades into the late 21st century to limit the cumulative CO_2 emissions to 2.2 trillion tons (or 0.6 trillion tons of carbon). The CES of 16 Gt of CO_2 per year will extract one-third of the 3.2 trillion tons of CO_2 (CES1t) that would have been added by human activities since the industrial era. To get a perspective on the enormity of this extraction, the 2010 fossil fuel CO_2 emission is 32 Gt of CO_2 per year. This case meets all three criteria with a small exception. First, the option meets the criteria of limiting the long-term warming below the dangerous level (<50% probability of exceeding 1.5 °C) and below the catastrophic level (<5% probability of exceeding 3 °C). Next, the end-of-century temperature curve is trending downward, providing great relief for the expected sea level rise during centuries beyond 2100. The one exception is that this case does not limit the near-term warming below the dangerous level (with an "overshoot" at 2050) (6).

Summary

Basically, for a safe climate, all three levers (CN, SP, and CES) must be deployed as soon as possible. The CN and SP levers must be deployed by 2030 and 2020, respectively; the cumulative CO_2 emissions from preindustrial must be limited to 2.2 trillion tons of CO_2 (or 0.6 trillion tons of carbon); and the CES lever should extract and sequester as much as 1 trillion tons of CO_2 (CES1t), depending on when the CN lever is deployed. If the CN lever is deployed as early as 2020, the required CES is much less than 1 trillion tons.

We propose that mitigation goals be set in terms of climate risk category instead of a temperature threshold. In this paper, we offer three broad risk categories, but it is likely that a more granular set of categories is required. The temperature threshold has served policy very well; however, given the imminence of dangerous warming within decades, the focus must broaden to include extreme climate changes. Precipitation, flooding, fire, and drought will all become serious sources of concern. The temperature will still occupy our attention because of the heat stress phenomenon and the likelihood of approximately half of the population exposed to deadly heat by 2050 (Box 2).

We conclude with a commentary on the feasibility of the mitigation options considered thus far. Over 24 technological measures to reduce SLCPs have been detailed previously (39) (details are provided in *SI Appendix*). These measures include providing clean cook stoves to the poorest three billion of the world's total population and installing particulate filters in all diesel vehicles to reduce global BC emissions by nearly 80% and also reduce air pollution-related mortalities by ∼2 million; routine maintenance of gas pipes and banning gas flaring to reduce methane leaks; recovering methane from landfills, water sewage treatment plants, and farm manure; replacing HFCs with other available refrigerants that have negligible greenhouse effects; and installing catalytic converters in vehicles to reduce emissions of ozone precursors.

CN levers require switching from fossil fuels to renewables such as wind, solar, geothermal and nuclear sources, among others. Also, CO_2 emissions from industrial processes should be eliminated. This requires electrification of all end uses and production of electricity from renewables (40). Since many renewables (solar and wind) are intermittent, storage is a crucial issue. Batteries, hydrogen production by renewables, and pumped hydropower are all possible options for storage. While about 50% of reductions are possible with scaling up of existing technologies, innovations are required for achieving carbon neutrality in a cost-effective manner (40). Achievement of carbon neutrality also requires societal transformation, governance, and market mechanisms such as cap and trade and carbon pricing (40). The encouraging sign is that 52 cities, 65 businesses, and numerous universities have already embarked on the CN pathway (41). Some of these living laboratories, like California and Stockholm, have shown that the gross domestic product (GDP) can be decoupled from carbon emissions. Their carbon emission per GDP has decreased by 20% while bending the carbon emissions curve. The technology development and innovations from these living laboratories should be scaled to the world to greatly accelerate efforts to achieve CN within decades.

Of the three levers recommended here, the third lever dealing with CES is the most challenging and formidable due to lack of scalable technologies. However, many technologies are being explored, including capturing CO_2 in bioenergy power plants (42), biochar production by pyrolysis and storage in soils (43), restoration of soil organic pools (44), chemical weathering of rocks, mineral sequestration, reforestation, and urban forestry, among others. The availability of land and conflict with food production is another important constraint in some of the CES solutions. Major breakthroughs are needed urgently, and in the meantime, the best option is to start on the CN goal by 2020 and mitigate the SPs as soon as possible, since cost-effective technologies are already present to immediately start bending the emission curves.

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