Climate change impacts are sensitive to the concentration stabilization path

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Analysis of policies to achieve the long-term objective of the United Nations Framework Convention on Climate Change, stabilizing concentrations of greenhouse gases at levels that avoid "dangerous" climate changes, must discriminate among the infinite number of emission and concentration trajectories that yield the same final concentration. Considerable attention has been devoted to path-dependent mitigation costs, generally for CO_2 alone, but not to the differential climate change impacts implied by alternative trajectories. Here, we derive pathways leading to stabilization of equivalent CO_2 concentration (including radiative forcing effects of all significant trace gases and aerosols) with a range of transient behavior before stabilization, including temporary overshoot of the final value. We compare resulting climate changes to the sensitivity of representative geophysical and ecological systems. Based on the limited available information, some physical and ecological systems appear to be quite sensitive to the details of the approach to stabilization. The likelihood of occurrence of impacts that might be considered dangerous increases under trajectories that delay emissions reduction or overshoot the final concentration.

The objective of avoiding "dangerous anthropogenic interference with the climate system," stated in Article 2 of the Framework Convention on Climate Change, is a potential organizing principle for long-term international climate policy. Attempts to define limits to warming predate the signing of the Framework Convention in 1992 (1); more recently, the Intergovernmental Panel on Climate Change (IPCC) has proposed five reasons for concern involving ecological, geophysical, and socio-economic consequences of climate change that could be considered relevant to interpreting Article 2 (2). Several studies have attempted to connect either particular impacts (3) or the IPCC reasons for concern more broadly (4, 5) to particular levels or rates of climate change. However, assessing the levels and rates of climate change that might engender significant risks of triggering dangerous impacts remains an important goal.

Scenarios that stabilize greenhouse gas concentrations in the atmosphere (6–9) may serve as tools for exploring the tradeoffs between climate change impacts on the one hand, and the costs of emissions reductions needed to achieve stabilization on the other. Although evaluating this tradeoff for different stabilization levels is essential, it is also important to investigate how the tradeoff may change across different atmospheric pathways to the same ultimate stabilization level.

Qualitative arguments (9) emphasizing the potential benefits of delaying emissions reductions required to achieve stabilization have been quantified by using economic optimization models (10–12). However, Article 2 of the Framework Convention involves a broader conception of damages (1–3) than is captured by these models. With few exceptions (13, 14), the effects of climate thresholds and abrupt change have been omitted from derivation of optimal paths. Furthermore, damage functions used in current economic models are highly aggregated and do not adequately account for the effect of differing rates of climate change that would arise from different paths to a final concentration.

We assess how the potential for dangerous climate impacts may change across different pathways to stabilization of greenhouse gas concentrations. In the first section, we define a range of alternative multigas stabilization pathways that differ not only in their final stabilization level, but also in their transient pathways to stabilization. We model the implications of these alternative pathways for levels and rates of global average temperature change over the next two centuries. In the second section, we assess the implications of the differences in climate change across these various stabilization pathways for impacts that might be considered dangerous, including effects on niche ecosystems, distintegration of the West Antarctic and Greenland ice sheets, shutdown of the Thermohaline Circulation (THC), and stresses on food production and water supply.

Paths to Stabilization

To assess the differences in climate change outcomes implied by alternative pathways to stabilization of atmospheric concentrations, we define slow change (SC), rapid change (RC), and overshoot (OS) pathways leading to stabilization of equivalent CO_2 concentrations at 500, 600, and 700 ppm. We will refer, for example, to a SC pathway stabilizing at 500 ppm as an SC500 pathway, a RC trajectory to 600 ppm as an RC600 pathway, etc. These pathways differ from existing sets of stabilization scenarios (7, 9, 10) in that they include all significant radiatively active trace gases and aerosols (15), rather than CO_2 only, and also explore a wider range of possible approaches to stabilization. Overshoot of final CO_2 concentration has been an outcome of previous model analyses of least-cost paths to stabilization (12, 16) and has also been explicitly specified in carbon cycle analyses of stabilization pathways to illustrate the possibility that favorable tradeoffs between reduced mitigation costs and increased climate change damages may be associated with pathways that temporarily exceed their ultimate stabilization level (17).

Equivalent CO_2 concentration is a measure of radiative forcing expressed in terms of the concentration of CO_2 that would produce an amount of forcing equivalent to the total forcing from all gases and aerosols combined. We define the equivalent CO_2 level to be equal to the true CO_2 level in 2000 (ref. 18 and see also *Supporting Text*, which is published as supporting information on the PNAS web site). Therefore, the equivalent CO_2 levels in our stabilization scenarios indicate how much the true CO_2 level would have to increase, relative to its level in 2000, to produce the same increase in forcing caused by the combined effect of all radiatively active trace gases and aerosols. With this approach, future equivalent CO_2 concentrations can be more easily compared to CO_2-only scenarios (9).

Specification of Stabilization Pathways. Each type of stabilization pathway is defined by using a set of standardized specification

Abbreviations: TAR, Third Assessment Report; SRES, Special Report on Emissions Scenarios; IPCC, Intergovernmental Panel on Climate Change; SC, slow change; RC, rapid change; OS, overshoot; THC, Thermohaline Circulation.

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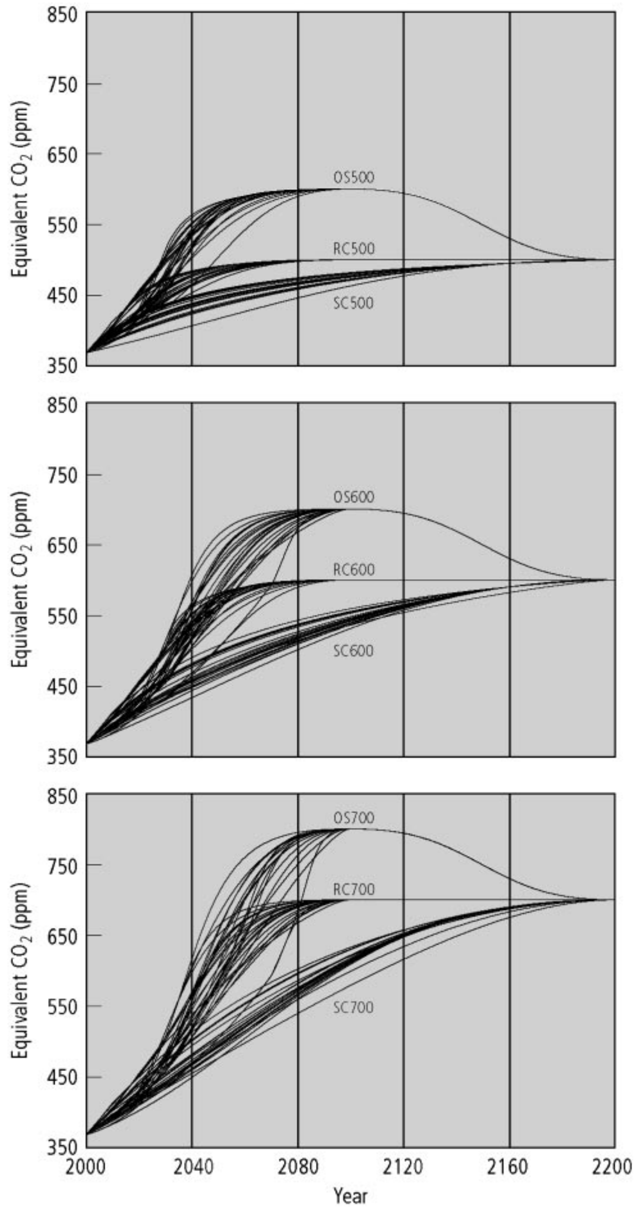

Fig. 1. Equivalent CO_2 stabilization scenarios for 500 (*Top*), 600 (*Middle*), and 700 (*Bottom*) ppm, showing SC, RC, and OS pathways.

rules described in detail below. RC pathways are assumed to follow reference scenarios until at least 2030 before departing and achieving stabilization in 2100 (Fig. 1). SC pathways are assumed to follow reference scenarios until at least 2005 before departing and achieving stabilization in 2200. OS pathways follow rapid approaches to a level in 2100 that is 100 ppm above the ultimate stabilization level, and then decline to the stabilization level in 2200.

Reference scenarios for equivalent CO_2 concentration are based on 25 scenarios from the Special Report on Emissions Scenarios (SRES; ref. 19) that provide emissions projections for the Kyoto gases (CO_2, CH_4, N_2O, hydrofluorocarbons, perfluorocarbons, and SF_6), the Montreal gases (chlorofluorocarbons, hydrochlorofluorocarbons, carbon tetrachloride, methyl chloroform, and brominated gases), sulfate aerosols, and the reactive gases (CO, NOx, and volatile organic compounds). Using a range of reference paths (18) is particularly important in adequately reflecting uncertainty in rates of climate change over the next several decades. SRES CO_2 emissions from fossil fuel burning and land use change are adjusted to be consistent with more recent data. These adjustments roughly double the magnitude of net emissions from land use change and decrease fossil fuel emissions by 4% in the year 2000 (see *Supporting Text*).

The functional form of the concentration stabilization pathways is defined by Padé approximants (ratios of polynomials) (6), to be comparable with existing CO_2-only stabilization pathways (9). These functions require defining a concentration level at a control point that lies between the departure and stabilization dates. Here, the control point is initially set to be equal to a concentration 10 ppm below the stabilization level 40 years before stabilization, to ensure that paths do not effectively stabilize much earlier than the specified date. If these parameter values produce a path that exceeds the reference scenario at any point, the control point is adjusted downward in 1-ppm increments until the stabilization path lies below the reference path at all times. This allows characteristics of the reference scenario to influence the stabilization path even beyond the departure date.

For paths that stabilize in 2100 (i.e., RC pathways), we eliminate reference scenarios that do not reach the stabilization level by the stabilization date. For paths that stabilize in 2200 (i.e., SC and OS pathways), we eliminate reference scenarios that have not reached the stabilization level by 2100 and are declining in 2100, assuming that they would not rise again beyond 2100. We assume in both cases that mitigation would not be required to achieve the stabilization goals. However, we keep reference paths that exceed the stabilization level but then decline below it before 2100, reasoning that mitigation would be required in earlier years to avoid exceeding the stabilization level. In these cases the stabilization path is allowed to exceed the reference path after the point at which the reference path crosses, and falls below, the stabilization level.

In some cases, specifying a control point such that the stabilization path lies below the reference path produces a discontinuous function, because the Padé approximant functional form is not infinitely flexible. When this occurs, we increase by one the year in which departure from the reference path occurs, until a successful stabilization path is achieved. If this procedure causes the date of departure from the reference scenario to become later than the year in which the control point is defined, we move the control point forward by 10 years (i.e., to 30 years before the stabilization date), and start the specification process over again. Essentially, this process allows the stabilization path to follow the reference scenario for a longer period when departing from it would require concentrations in later years to increase above the reference scenario to achieve stabilization.

To stabilize at 500 ppm equivalent CO_2, the 2030 departure date in the RC case is already too late to allow smooth paths to stabilization to be defined that meet our criteria. We therefore move the departure to 2010, so that all reference scenarios can produce successful stabilization paths. For similar reasons, we move the departure date for the SC500 pathways to 2000.

Greenhouse Gas Cycle and Simple Climate Models. Reference concentration paths are calculated from the SRES emissions scenarios by using the same greenhouse gas cycle models used in the IPCC Third Assessment Report (TAR). The carbon cycle model is a 1D upwelling-diffusion model of the global ocean with polar overturning, coupled with a well mixed atmosphere and a six-box terrestrial biosphere model (20, 21). Its calibration and the implications for adjustments to SRES assumptions regarding net emissions from land use change are described in *Supporting Text*.

The methane model is based on a variable lifetime dictated by the OH concentration, which is itself modeled as a function of emissions of NOx, CO, and volatile organic compound by using the formula provided in table 4.11 of TAR (22). The N_2O model is also based on a variable lifetime, which is a function of N_2O atmospheric abundance as described in table 4.5 of TAR (22). Tropospheric ozone is modeled as a function of methane concentrations and OH concentrations (22). Perfluorocarbons, SF_6, hydrofluorocarbons, and hydrochlorofluorocarbons are modeled as constant lifetime removal processes by using lifetimes from table 6.7 of TAR (23).

Concentrations of the various gases are converted to radiative forcing (and then to equivalent CO_2 concentrations) by using relationships for CO_2, CH_4, N_2O, hydrofluorocarbons, perfluorocarbons, SF_6, and tropospheric O_3 from TAR (23). In addition, the effect of methane oxidation on stratospheric water vapor is included by scaling the direct effect of CH_4 by a factor of 1.05. For the Montreal gases, the sum of positive radiative forcing for all species with significant forcing is taken from TAR WG1 appendix II, table 2.3.9 (23). The negative forcing caused by stratospheric ozone depletion is modeled (24) based on the equivalent effective stratospheric chlorine loading resulting from these gases, as provided in appendix 2 of the TAR WG1 report, table 2.2.10 (23).

Direct forcing caused by sulfate aerosols is scaled linearly, and indirect forcing logarithmically, with SO_2 emissions (24). The reference level is the estimate of 1990 forcing, taken to be -0.3 W/m^2 for direct forcing and -0.8 for indirect forcing (25). Radiative forcing from organic and black carbon from fossil fuel sources are scaled with SO_2 emissions (24). Forcing in 1990 is assumed to be -0.1 W/m^2 for organic carbon and $+0.2$ W/m^2 for black carbon (24). Radiative forcing from organic and black carbon from biomass burning is scaled with net deforestation.

Changes in global mean temperature are calculated with a simple climate model of the type used in TAR (26). It consists of a well mixed atmosphere that exchanges heat with the land surface and ocean, which is represented as a 1D column with upwelling and diffusive mixing, as well as polar overturning. Modeled surface temperature response to changes in concentrations of radiatively active gases and aerosols is driven by the global energy balance at the surface and the thermal inertia of the ocean. Although this model is of a type well suited and commonly used to simulate the behavior of more complex climate models under a wide range of conditions (27), it should be noted that it does not capture climate shifts associated with changes in large-scale ocean circulation or processes like the effect of ice sheet disintegration on albedo.

Results. Results (Fig. 2 and Table 1) show that temperature change over the period 2000–2200 differs substantially across the SC, RC, and OS pathways. For example, the range of temperature outcomes in 2100 across the three types of approaches for a given stabilization level is ≈0.5–1.2°C, as large as, or larger than, the difference in long-term outcomes for different stabilization levels. Even after excluding the OS pathways, the range of outcomes in 2100 is ≈0.1–0.6°C, more than half the range caused by variation in the stabilization level. Beyond ≈2250, global average temperature change is identical across the three types of approaches and differs only across stabilization levels. This result is subject to the caveat, noted above, that simple climate models do not capture the potential for climate shifts that could be induced by exceeding geophysical thresholds. Temperature change in 2300 is higher by 0.2–0.9°C for each 100-ppm increase in stabilization level, depending on the climate sensitivity (the high end of the range is associated with higher sensitivity and lower absolute levels of equivalent CO_2, caused by nonlinear forcing-concentration relationships).

SC pathways lead to median rates of temperature change that decline over time from an initial rate of 0.16°C per decade (Fig. 3), assuming a climate sensitivity of 2.5°C (23). For low stabilization levels (SC500) median rates of change ultimately fall below 0.1°C per decade. For high stabilization levels (SC700), they remain ≈0.15°C per decade or above.

RC and OS paths produce rates of temperature change that are substantially higher than those in the SC case (Fig. 3). For example, in the RC500 case the peak in the median rate of change is ≈0.2°C

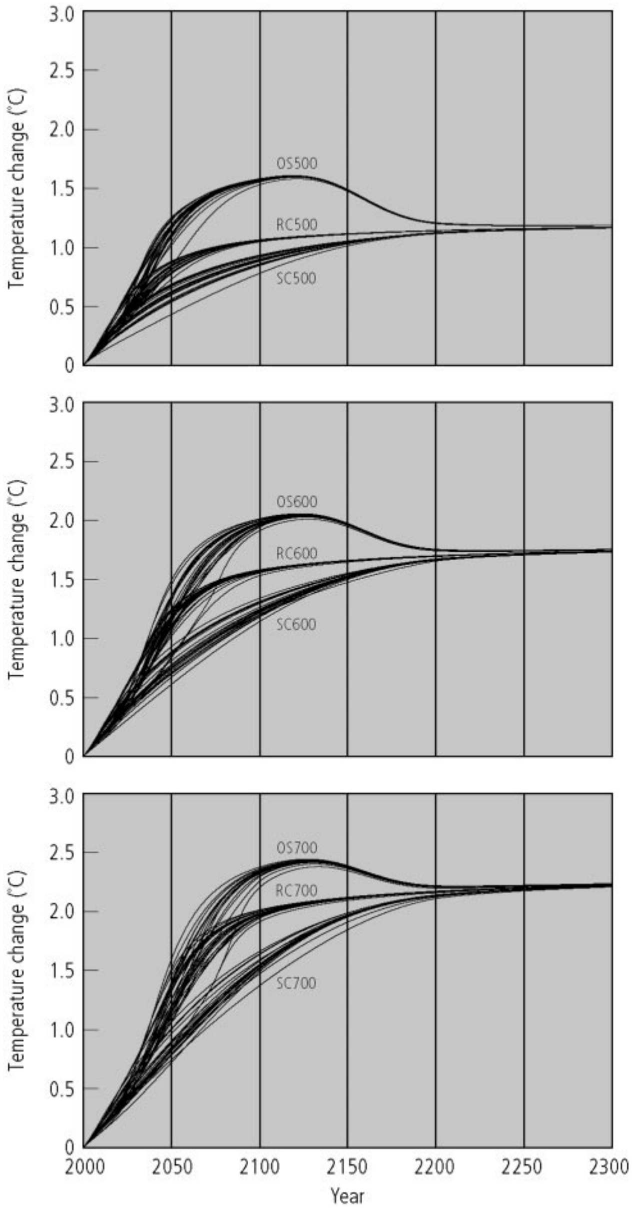

Fig. 2. Global average temperature change, 2000–2300, for SC, RC, and OS pathways to 500 (*Top*), 600 (*Middle*), and 700 (*Bottom*) ppm equivalent CO_2, assuming a climate sensitivity of 2.5°C. Results for other climate sensitivities are summarized in Table 1.

Table 1. Global average temperature change in 2300 and peak in OS scenarios (in parentheses)

Stabilization level, ppm	Climate sensitivity 1.5°C	2.5°C	4.5°C
500	0.7 (1.0)	1.2 (1.6)	2.0 (2.6)
600	1.1 (1.3)	1.7 (2.0)	2.9 (3.2)
700	1.4 (1.5)	2.2 (2.4)	3.7 (3.8)

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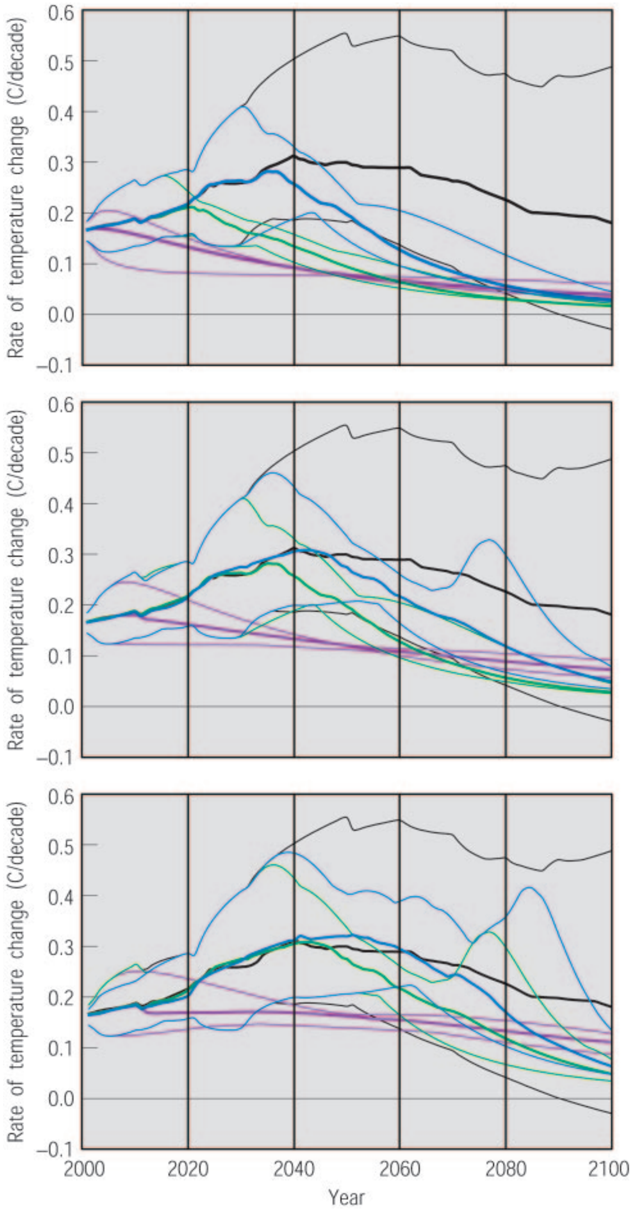

Fig. 3. Distributions of rates of temperature change, in °C per decade, for SRES (black), SC (violet), RC (green), and OS (blue) pathways, to 500 (*Top*), 600 (*Middle*), and 700 (*Bottom*) ppm equivalent CO_2, assuming a climate sensitivity of 2.5°C. Thick lines show medians, and thin lines show maximum and minimum values over time.

per decade. For RC600 and RC700, the median rate of change approaches 0.3°C per decade, and rates >0.2°C per decade are sustained for 30–40 years. Results are sensitive to the reference scenario: maximum rates of change in both SC and RC pathways can be 0.05–0.15°C per decade higher than median rates of change, driven by those reference scenarios that imply relatively rapid increases in equivalent CO_2 concentrations. Results are also sensitive to the assumed climate sensitivity. For a sensitivity of 4.5°C (data not shown), the median rate of temperature change reaches 0.4°C per decade in the RC600 and RC700 cases and remains >0.2°C per decade for 60–80 years.

Later in the century, the rate of change in temperature is generally lower, rather than higher, in the RC pathways. However, the difference is quite small, and rates of change in both the RC and SC pathways are relatively low by that time.

The results for OS pathways show that OS can lead to substantial additional warming (see Table 1), ranging from 0.1°C to 0.6°C above what otherwise would occur. The low end of this range is associated with higher stabilization levels and low climate sensitivity. In addition, OS scenarios have higher rates of temperature change, which are sustained longer, than do pathways that do not overshoot. For example, for stabilization at 600 ppm, the median rate of change in the RC pathways peaks at 0.29°C per decade and remains >0.2°C per decade for ≈35 years (2015–2050). In the OS case, the peak rate of change increases to 0.32°C per decade, and the rate remains >0.2°C per decade for an additional 15 years (2015–2065).

Impact Assessment

Magnitude of Warming. Temporary exceedance of a threshold temperature for a large-scale physical or biological process (2, 3, 28) could entail widespread damage. Coral reefs, and other niche ecosystems, may be sensitive to modest increases in temperature (2, 29). Model studies suggest that Earth may enter an era of sustained bleaching and widespread demise of reefs if global mean temperature increases by >1°C from recent levels. The eventual degree of adaptation, acclimation, and reestablishment of reefs is uncertain (30) and would likely depend on the rate of warming (see below).

Thresholds could be defined for complete loss of spatially limited ecosystems such as tundra, cloud forests, or one or more small islands via sea-level rise and total submergence. Because of the large inertia in the thermal expansion component of sea-level rise, it is unlikely that the latter impact is sensitive to century scale differences in transient temperatures or rates of the magnitude discussed here (8). However, if major ice sheets respond to warming through fast mechanisms (31–33), transient temperatures could indeed matter.

The Greenland ice sheet would have no steady state and would lose its entire ice mass over the course of millennia for local warming exceeding 3°C (which corresponds to a smaller global warming in simulations of future climate, see ref. 34), according to one ice sheet model (35). The large thermal inertia of the ice sheet would appear to dampen the significance of transient temperature differences over modest (≈100 years) time scales. However, Zwally *et al.* (32) argue that dynamical processes not incorporated in current models accelerate ice loss once a threshold temperature sufficient to cause surface melting is attained. The mass balance of the West Antarctic ice sheet is controlled by ice streams that are difficult to model. Global mean warming exceeding 2–4°C relative to current temperature may be sufficient to cause disintegration of ice shelves, acceleration of ice streams, and loss of the ice sheet (36).

Using a simplified ocean model, Stocker and Schmittner (37) predicted a shutdown of the THC for global warming exceeding ≈3°C over 100 years. The specific limit depends on the rate of warming in their model (see below). Because the temperature-rate domain has not been fully explored with atmosphere-ocean general circulation models (AOGCMs), the robustness of this result is difficult to judge. However, most AOGCMs exhibit a slowdown of the THC during this century absent abatement policy.

Absent thresholds, modest temperature differences may still have marked effects on impacts (36). Large increases in damage to particular coastal, boreal, tropical, and other ecosystems can arise from small temperature increases (<1°C) within the 1–3°C range above the recent global mean (38, 39). Projections of population size at risk of hunger, malaria, and coastal flooding indicate a relatively gradual increase in vulnerability as a function of CO_2 concentration or temperature at stabilization (40, 41). In contrast, one study (40) found that the population at risk of water shortage in vulnerable regions late in this century rises by a factor of 3–4 when comparing paths to stabilizing concentration at 550 ppm vs. 450 ppm and a factor of 8 when comparing paths to stabilization at 650 ppm vs. 450 ppm. Increases in frequency of local extremes may also have considerable consequences but quantitative links to global mean temperature changes are not available.

Comparison of potential impacts to the absolute temperature differences in Table 1 and Figs. 1 and 2 suggests several examples where differences between SC, RC, and OS trajectories could translate into large differences in impacts. Warming in SC and RC cases differs from OS by ≈0.5°C for 500 ppm for a sustained period, an amount that might substantially increase the extent of coral reef bleaching if reefs are indeed sensitive to small temperature increments >1°C. Examination of Fig. 2 suggests that other ecosystems that are sensitive to differences of warming of <1°C in the 1–3°C range (38, 39) would experience markedly different impacts for OS, RC, and SC cases. Differences in temperature of 0.5–1.0°C are maintained for 50–100 years for each concentration case studied.

Comparison of the concentration differences between SC or RC versus OS cases for 500 ppm with the results of ref. 40 suggests an order-of-magnitude increase in people at risk of water shortages by the 2080s in the OS case, to ≈150 million people under one assumption about future socio-economic conditions. Major ice sheets may also be significantly more vulnerable in OS cases because of possible polar amplification of apparently small changes in the global mean temperature. For example, local warming at Greenland is projected to be 1.2–3.1 times the global mean temperature increase (34). The upper end of this range would translate into a local warming of 4.7°C in the OS500 case lasting about a century, versus a maximum of 3.7°C in the SC or RC cases. Such a difference might substantially increase ice sheet decay if fast processes (31–33) are an important factor in ice dynamics.

Rate of Warming. Differences in transient rates of warming could significantly affect outcomes for ecosystems. Early attempts to develop limits on warming by using an ecological perspective focused on the competition between rates of temperature or sea-level change and rates of species or ecosystem adjustment for midlatitude forests, coral reefs, and wetlands through migration, seed dispersal, or structural change (42). It was estimated that sustained rates of warming >0.1°C per decade and >2 cm per decade sea-level rise may exceed the adaptive capacity of some sensitive ecosystems. A recent assessment (39) indicates little change in overall understanding of this question, perhaps because surprisingly few such comparisons have been published in the past decade (2).

Stocker and Schmittner (37) used rate of warming and absolute temperature change to test the sensitivity of the THC to shut down in a simplified ocean model. A crude summary of their results is that the THC collapses for warming in excess of 0.3°C per decade sustained for a century. Such rates and amounts of warming might be achieved for 700 ppm in the RC and OS cases with high climate sensitivity. Although none of the cases explored in Fig. 3 entirely avoid rates of warming that may be problematic for sensitive ecosystems (>0.01°C per year), the exposure time to such rates of change increases substantially for the RC and OS cases.

Conclusions

Based on the limited available information, it appears that some physical and ecological systems may be quite sensitive to the details of the approach to stabilization. RC and OS pathways imply rates of temperature change that, for several decades, exceed or are near the upper end of the range of rates to which ecosystems are known to be able to adapt. Incremental warming on pathways that overshoot the stabilization level by 100 ppm may significantly increase the risk of exceeding critical climate thresholds. A challenge for research is to define such temperatures and rates more precisely. In the real world, the shape of trajectories is only one factor in determining the risk associated with a given trajectory. Uncertainty and regional climate variability will smear any idealized limit that is based on global mean temperature.

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