Irreversible climate change due to carbon dioxide emissions

Susan Solomon[a,1], **Gian-Kasper Plattner**[b], **Reto Knutti**[c], **and Pierre Friedlingstein**[d]

[a]Chemical Sciences Division, Earth System Research Laboratory, National Oceanic and Atmospheric Administration, Boulder, CO 80305; [b]Institute of Biogeochemistry and Pollutant Dynamics and [c]Institute for Atmospheric and Climate Science, ETH CH-8092, Zurich, Switzerland; and [d]Institut Pierre Simon Laplace/Laboratoire des Sciences du Climat et de l'Environnement, Unité Mixte de Recherche 1572 Commissariat à l'Energie Atomique–Centre National de la Recherche Scientifique–Université Versailles Saint-Quentin, Commissariat a l'Energie Atomique-Saclay, l'Orme des Merisiers, 91191 Gif sur Yvette, France

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The severity of damaging human-induced climate change depends not only on the magnitude of the change but also on the potential for irreversibility. This paper shows that the climate change that takes place due to increases in carbon dioxide concentration is largely irreversible for 1,000 years after emissions stop. Following cessation of emissions, removal of atmospheric carbon dioxide decreases radiative forcing, but is largely compensated by slower loss of heat to the ocean, so that atmospheric temperatures do not drop significantly for at least 1,000 years. Among illustrative irreversible impacts that should be expected if atmospheric carbon dioxide concentrations increase from current levels near 385 parts per million by volume (ppmv) to a peak of 450–600 ppmv over the coming century are irreversible dry-season rainfall reductions in several regions comparable to those of the ''dust bowl'' era and inexorable sea level rise. Thermal expansion of the warming ocean provides a conservative lower limit to irreversible global average sea level rise of at least 0.4–1.0 m if 21st century CO_2 concentrations exceed 600 ppmv and 0.6–1.9 m for peak CO_2 concentrations exceeding ≈1,000 ppmv. Additional contributions from glaciers and ice sheet contributions to future sea level rise are uncertain but may equal or exceed several meters over the next millennium or longer.

dangerous interference | precipitation | sea level rise | warming

Over the 20th century, the atmospheric concentrations of key greenhouse gases increased due to human activities. The stated objective (Article 2) of the United Nations Framework Convention on Climate Change (UNFCCC) is to achieve stabilization of greenhouse gas concentrations in the atmosphere at a low enough level to prevent "dangerous anthropogenic interference with the climate system." Many studies have focused on projections of possible 21st century dangers (1–3). However, the principles (Article 3) of the UNFCCC specifically emphasize "threats of serious or irreversible damage," underscoring the importance of the longer term. While some irreversible climate changes such as ice sheet collapse are possible but highly uncertain (1, 4), others can now be identified with greater confidence, and examples among the latter are presented in this paper. It is not generally appreciated that the atmospheric temperature increases caused by rising carbon dioxide concentrations are not expected to decrease significantly even if carbon emissions were to completely cease (5–7) (see Fig. 1). Future carbon dioxide emissions in the 21st century will hence lead to adverse climate changes on both short and long time scales that would be essentially irreversible (where irreversible is defined here as a time scale exceeding the end of the millennium in year 3000; note that we do not consider geo-engineering measures that might be able to remove gases already in the atmosphere or to introduce active cooling to counteract warming). For the same reason, the physical climate changes that are due to anthropogenic carbon dioxide already in the atmosphere today are expected to be largely irreversible. Such climate changes will lead to a range of damaging impacts in different regions and sectors, some of which occur promptly in association with warming, while others build up under sustained warming because of the time lags of the processes involved. Here we illustrate 2 such aspects of the irreversibly altered world that should be expected. These aspects are among reasons for concern but are not comprehensive; other possible climate impacts include Arctic sea ice retreat, increases in heavy rainfall and flooding, permafrost melt, loss of glaciers and snowpack with attendant changes in water supply, increased intensity of hurricanes, etc. A complete climate impacts review is presented elsewhere (8) and is beyond the scope of this paper. We focus on illustrative adverse and irreversible climate impacts for which 3 criteria are met: (*i*) observed changes are already occurring and there is evidence for anthropogenic contributions to these changes, (*ii*) the phenomenon is based upon physical principles thought to be well understood, and (*iii*) projections are available and are broadly robust across models.

Advances in modeling have led not only to improvements in complex Atmosphere–Ocean General Circulation Models (AOGCMs) for projecting 21st century climate, but also to the implementation of Earth System Models of Intermediate Complexity (EMICs) for millennial time scales. These 2 types of models are used in this paper to show how different peak carbon dioxide concentrations that could be attained in the 21st century are expected to lead to substantial and irreversible decreases in dry-season rainfall in a number of already-dry subtropical areas and lower limits to eventual sea level rise of the order of meters, implying unavoidable inundation of many small islands and low-lying coastal areas.

Results

Longevity of an Atmospheric CO_2 Perturbation. As has long been known, the removal of carbon dioxide from the atmosphere involves multiple processes including rapid exchange with the land biosphere and the surface layer of the ocean through air–sea exchange and much slower penetration to the ocean interior that is dependent upon the buffering effect of ocean chemistry along with vertical transport (9–12). On the time scale of a millennium addressed here, the CO_2 equilibrates largely between the atmosphere and the ocean and, depending on associated increases in acidity and in ocean warming (i.e., an increase in the Revelle or "buffer" factor, see below), typically ≈20% of the added tonnes of CO_2 remain in the atmosphere while ≈80% are mixed into the ocean. Carbon isotope studies provide important observational constraints on these processes and time constants. On multimillenium and longer time scales, geochemical and geological

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[1]To whom correspondence should be addressed. E-mail: susan.solomon@noaa.gov.

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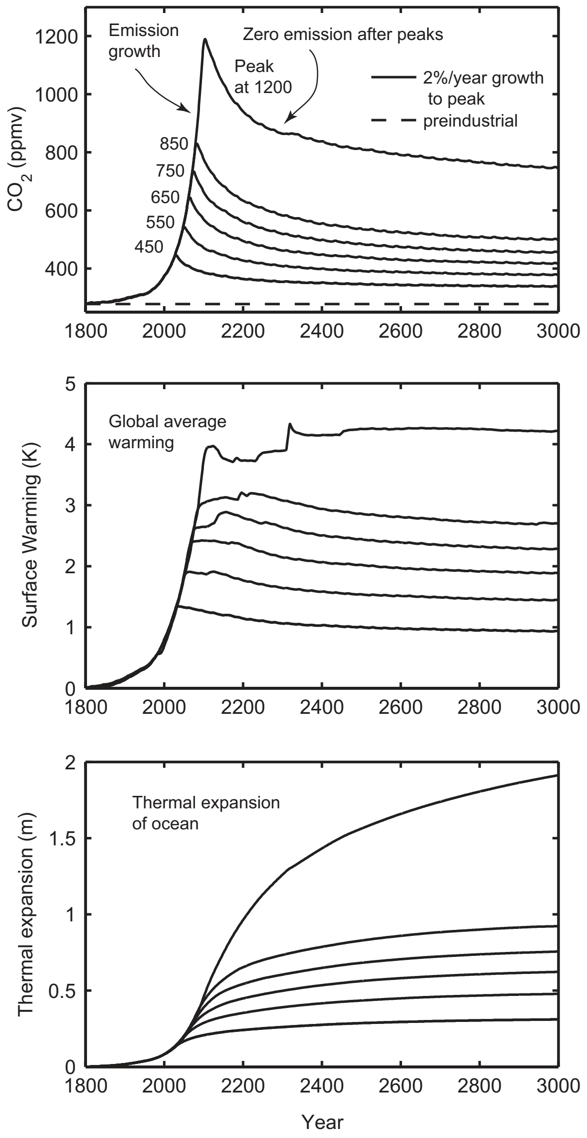

Fig. 1. Carbon dioxide and global mean climate system changes (relative to preindustrial conditions in 1765) from 1 illustrative model, the Bern 2.5CC EMIC, whose results are comparable to the suite of assessed EMICs (5, 7). Climate system responses are shown for a ramp of CO$_2$ emissions at a rate of 2%/year to peak CO$_2$ values of 450, 550, 650, 750, 850, and 1200 ppmv, followed by zero emissions. The rate of global fossil fuel CO$_2$ emission grew at $\approx$1%/year from 1980 to 2000 and $>$3%/year in the period from 2000 to 2005 (13). Results have been smoothed using an 11-year running mean. The 31-year variation seen in the carbon dioxide time series is introduced by the climatology used to force the terrestrial biosphere model (15). (*Top*) Falloff of CO$_2$ concentrations following zero emissions after the peak. (*Middle*) Globally averaged surface warming (degrees Celsius) for these cases (note that this model has an equilibrium climate sensitivity of 3.2 °C for carbon dioxide doubling). Warming over land is expected to be larger than these global averaged values, with the greatest warming expected in the Arctic (5). (*Bottom*) Sea level rise (meters) from thermal expansion only (not including loss of glaciers, ice caps, or ice sheets).

processes could restore atmospheric carbon dioxide to its preindustrial values (10, 11), but are not included here.

Fig. 1 illustrates how the concentrations of carbon dioxide would be expected to fall off through the coming millennium if manmade emissions were to cease immediately following an illustrative future rate of emission increase of 2% per year [comparable to observations over the past decade (ref. 13)] up to peak concentrations of 450, 550, 650, 750, 850, or 1,200 ppmv; similar results were obtained across a range of EMICs that were assessed in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (5, 7). This is not intended to be a realistic scenario but rather to represent a test case whose purpose is to probe physical climate system changes. A more gradual reduction of carbon dioxide emission (as is more likely), or a faster or slower adopted rate of emissions in the growth period, would lead to long-term behavior qualitatively similar to that illustrated in Fig. 1 (see also Fig. S1). The example of a sudden cessation of emissions provides an upper bound to how much reversibility is possible, if, for example, unexpectedly damaging climate changes were to be observed.

Carbon dioxide is the only greenhouse gas whose falloff displays multiple rather than single time constants (see Fig. S2). Current emissions of major non-CO$_2$ greenhouse gases such as methane or nitrous oxide are significant for climate change in the next few decades or century, but these gases do not persist over time in the same way as carbon dioxide (14).

Fig. 1 shows that a quasi-equilibrium amount of CO$_2$ is expected to be retained in the atmosphere by the end of the millennium that is surprisingly large: typically $\approx$40% of the peak concentration enhancement over preindustrial values ($\approx$280 ppmv). This can be easily understood on the basis of the observed instantaneous airborne fraction (AF^{peak}) of $\approx$50% of anthropogenic carbon emissions retained during their buildup in the atmosphere, together with well-established ocean chemistry and physics that require $\approx$20% of the emitted carbon to remain in the atmosphere on thousand-year timescales [quasi-equilibrium airborne fraction (AF^{equi}), determined largely by the Revelle factor governing the long-term partitioning of carbon between the ocean and atmosphere/biosphere system] (9–11). Assuming given cumulative emissions, EMI, the peak concentration, $CO_2{}^{peak}$ (increase over the preindustrial value $CO_2{}^0$), and the resulting 1,000-year quasi-equilibrium concentration, $CO_2{}^{equi}$ can be expressed as

$$CO_2^{peak} = CO_2^0 + AF^{peak}{\cdot}EMI \qquad [1]$$

$$CO_2^{equi} = CO_2^0 + AF^{equi}{\cdot}EMI \qquad [2]$$

so that

$$CO_2^{equi} - CO_2^0 = \frac{AF^{equi}}{AF^{peak}}\,(CO_2^{peak} - CO_2^0). \qquad [3]$$

Given an instantaneous airborne fraction (AF^{peak}) of $\approx$50% during the period of rising CO$_2$, and a quasi-equilbrium airborne factor (AF^{equi}) of 20%, it follows that the quasi-equilibrium enhancement of CO$_2$ concentration above its preindustrial value is $\approx$40% of the peak enhancement. For example, if the CO$_2$ concentration were to peak at 800 ppmv followed by zero emissions, the quasi-equilibrium CO$_2$ concentration would still be far above the preindustrial value at $\approx$500 ppmv. Additional carbon cycle feedbacks could reduce the efficiency of the ocean and biosphere to remove the anthropogenic CO$_2$ and thereby increase these CO$_2$ values (15, 16). Further, a longer decay time and increased CO$_2$ concentrations at year 1000 are expected for large total carbon emissions (17).

Irreversible Climate Change: Atmospheric Warming. Global average temperatures increase while CO$_2$ is increasing and then remain approximately constant (within $\approx \pm$0.5 °C) until the end of the millennium despite zero further emissions in all of the test cases shown in Fig. 1. This important result is due to a near balance between the long-term decrease of radiative forcing due to CO$_2$ concentration decay and reduced cooling through heat loss to the oceans. It arises because long-term carbon dioxide removal

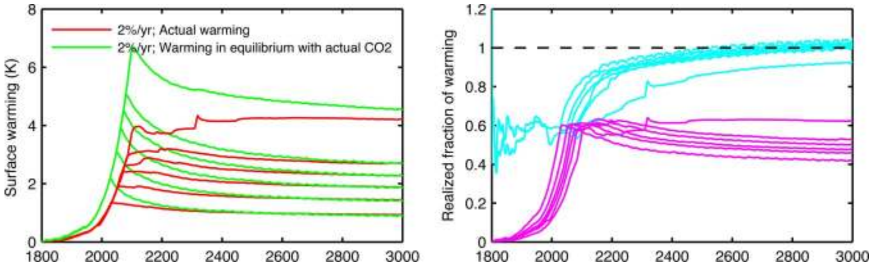

Fig. 2. Comparison between calculated time-dependent surface warming in the Bern2.5CC model and the values that would be expected if temperatures were in equilibrium with respect to the CO_2 enhancements, illustrative of 2%/year emission increases to 450, 550, 650, 750, 850, and 1,200 ppmv as in Fig. 1. (*Left*) The actual and equilibrium temperature changes (based upon the model's climate sensitivity at equilibrium). The cyan lines in *Right* show the ratio of actual and equilibrium temperatures (or realized fraction of the warming for the time-dependent CO_2 concentrations), while the magenta lines show the ratio of actual warming to the equilibrium temperature for the peak CO_2 concentration.

and ocean heat uptake are both dependent on the same physics of deep-ocean mixing. Sea level rise due to thermal expansion accompanies mixing of heat into the ocean long after carbon dioxide emissions have stopped. For larger carbon dioxide concentrations, warming and thermal sea level rise show greater increases and display transient changes that can be very rapid (i.e., the rapid changes in Fig. 1 *Middle*), mainly because of changes in ocean circulation (18). Paleoclimatic evidence suggests that additional contributions from melting of glaciers and ice sheets may be comparable to or greater than thermal expansion (discussed further below), but these are not included in Fig. 1.

Fig. 2 explores how close the modeled temperature changes are to thermal equilibrium with respect to the changing carbon dioxide concentration over time, sometimes called the realized warming fraction (19) (shown for the different peak CO_2 cases). Fig. 2 *Left* shows how the calculated warmings compare to those expected if temperatures were in equilibrium with the carbon dioxide concentrations vs. time, while Fig. 2 *Right* shows the ratio of these calculated time-dependent and equilibrium temperatures. During the period when carbon dioxide is increasing, the realized global warming fraction is ≈50–60% of the equilibrium warming, close to values obtained in other models (5, 19). After emissions cease, the temperature change approaches equilibrium with respect to the slowly decreasing carbon dioxide concentrations (cyan lines in Fig. 2 *Right*). The continuing warming through year 3000 is maintained at ≈40–60% of the equilibrium warming corresponding to the peak CO_2 concentration (magenta lines in Fig. 2 *Right*). Related changes in fast-responding atmospheric climate variables such as precipitation, water vapor, heat waves, cloudiness, etc., are expected to occur largely simultaneously with the temperature changes.

Irreversible Climate Change: Precipitation Changes. Warming is expected to be linked to changes in rainfall (20), which can adversely affect the supply of water for humans, agriculture, and ecosystems. Precipitation is highly variable but long-term rainfall decreases have been observed in some large regions including, e.g., the Mediterranean, southern Africa, and parts of southwestern North America (21–25). Confident projection of future changes remains elusive over many parts of the globe and at small scales. However, well-known physics (the Clausius–Clapeyron law) implies that increased temperature causes increased atmospheric water vapor concentrations, and changes in water vapor transport and the hydrologic cycle can hence be expected (26–28). Further, advances in modeling show that a robust characteristic of anthropogenic climate change is poleward expansion of the Hadley cell and shifting of the pattern of precipitation minus evaporation (*P–E*) and the storm tracks (22, 26), and hence a pattern of drying over much of the already-dry subtropics in a warmer world (≈15°-40° latitude in each hemisphere) (5, 26). Attribution studies suggest that such a drying pattern is already occurring in a manner consistent with models including anthropogenic forcing (23), particularly in the southwestern United States (22) and Mediterranean basin (24, 25).

We use a suite of 22 available AOGCM projections based upon the evaluation in the IPCC 2007 report (5, 29) to characterize precipitation changes. Changes in precipitation are expected (5, 20, 30) to scale approximately linearly with increasing warming (see Fig. S3). The equilibrium relationship between precipitation and temperature may be slightly smaller (by ≈15%) than the transient values, due to changes in the land/ocean thermal contrast (31). On the other hand, the observed 20th century changes follow a similar latitudinal pattern but presently exceed those calculated by AOGCMs (23). Models that include more complex representations of the land surface, soil, and vegetation interactively are likely to display additional feedbacks so that larger precipitation responses are possible.

Here we evaluate the relationship between temperature and precipitation averaged for each month and over a decade at each grid point. One ensemble member is used for each model so that all AOGCMs are equally weighted in the multimodel ensemble; results are nearly identical if all available model ensemble members are used.

Fig. 3 presents a map of the expected dry-season (3 driest consecutive months at each grid point) precipitation trends per degree of global warming. Fig. 3 shows that large uncertainties remain in the projections for many regions (white areas). However, it also shows that there are some subtropical locations on every inhabited continent where dry seasons are expected to become drier in the decadal average by up to 10% per degree of warming. Some of these grid points occur in desert regions that are already very dry, but many occur in currently more temperate and semiarid locations. We find that model results are more robust over land across the available models over wider areas for drying of the dry season than for the annual mean or wet season (see Fig. S4). The *Insets* in Fig. 3 show the monthly mean projected precipitation changes averaged over several large regions as delineated on the map. Increased drying of respective dry seasons is projected by >90% of the models averaged over the indicated regions of southern Europe, northern Africa, southern Africa, and southwestern North America and by >80% of the models for eastern South America and western Australia (see Fig. S3). Although given particular years would show exceptions, the long-term irreversible warming and mean rainfall changes as suggested by Figs. 1 and 3 would have important consequences in many regions. While some relief can be expected in the wet season for some regions (Fig. S4), changes in dry-season precipitation in northern Africa, southern Europe, and western Australia are expected to be near 20% for 2 °C warming, and those of southwestern North America, eastern South America, and southern Africa would be ≈10% for 2 °C of global mean warming. For comparison, the American "dust

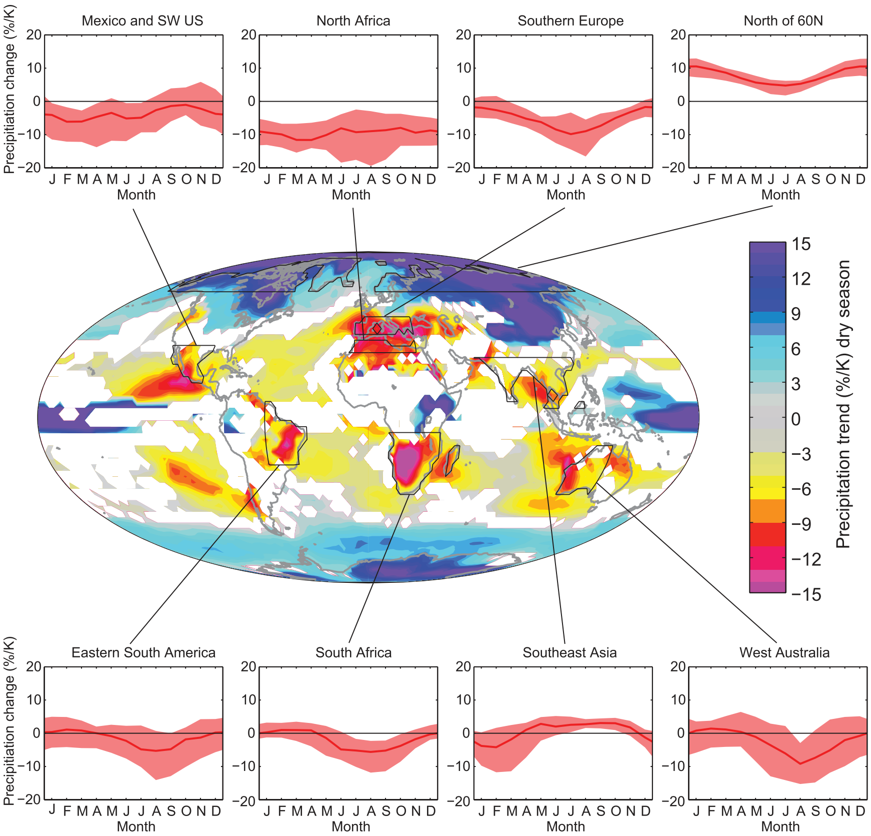

Fig. 3. Expected decadally averaged changes in the global distribution of precipitation per degree of warming (percentage of change in precipitation per degree of warming, relative to 1900–1950 as the baseline period) in the dry season at each grid point, based upon a suite of 22 AOGCMs for a midrange future scenario (A1B, see ref. 5). White is used where fewer than 16 of 22 models agree on the sign of the change. Data are monthly averaged over several broad regions in *Inset* plots. Red lines show the best estimate (median) of the changes in these regions, while the red shading indicates the ±1-σ likely range (i.e., 2 of 3 chances) across the models.

bowl” was associated with averaged rainfall decreases of ≈10% over ≈10–20 years, similar to major droughts in Europe and western Australia in the 1940s and 1950s (22, 32). The spatial changes in precipitation as shown in Fig. 3 imply greater challenges in the distribution of food and water supplies than those with which the world has had difficulty coping in the past. Such changes occurring not just for a few decades but over centuries are expected to have a range of impacts that differ by region. These include, e.g., human water supplies (25), effects on dry-season wheat and maize agriculture in certain regions of rain-fed farming such as Africa (33, 34), increased fire frequency, ecosystem change, and desertification (24, 35–38).

Fig. 4 *Upper* relates the expected irreversible changes in regional dry-season precipitation shown in Fig. 3 to best estimates of the corresponding peak and long-term CO_2 concentrations. We use 3 °C as the best estimate of climate sensitivity across the suite of AOGCMs for a doubling of carbon dioxide from preindustrial values (5) along with the regional drying values depicted in Fig. 3 and assuming that ≈40% of the carbon dioxide peak concentration is retained after 1000 years. Fig. 4 shows that if carbon dioxide were to peak at levels of ≈450 ppmv, irreversible decreases of ≈8–10% in dry-season precipitation would be expected on average over each of the indicated large regions of southern Europe, western Australia, and northern Africa, while a carbon dioxide peak value near 600 ppmv would be expected to lead to sustained rainfall decreases of ≈13–16% in the dry seasons in these areas; smaller but statistically significant irreversible changes would also be expected for southwestern North America, eastern South America, and Southern Africa.

Irreversible Climate Change: Sea Level Rise. Anthropogenic carbon dioxide will cause irrevocable sea level rise. There are 2 relatively well-understood processes that contribute to this and a third that may be much more important but is also very uncertain. Warming causes the ocean to expand and sea levels to rise as shown in Fig. 1; this has been the dominant source of sea level rise in the past decade at least (39). Loss of land ice also makes important contributions to sea level rise as the world warms. Mountain glaciers in many locations are observed to be retreating due to warming, and this contribution to sea level rise is also relatively well understood. Warming may also lead to large losses of the Greenland and/or Antarctic ice sheets. Additional rapid ice losses from particular parts of the ice sheets of Greenland and Antarctica have recently been observed (40–42). One recent study uses current ice discharge data to suggest ice sheet contributions of up to 1–2 m to sea level rise by 2100 (42), but other studies suggest that changes in winds rather than warming may account for currently observed rapid ice sheet flow (43), rendering quantitative extrapolation into the future uncertain. In addition to rapid ice flow, slow ice sheet mass balance processes are another mechanism for potential large sea level rise. Paleoclimatic data demonstrate large contributions of ice sheet loss to sea level rise (1, 4) but provide limited constraints on the rate of such processes. Some recent studies suggest that ice sheet surface mass balance loss for peak CO_2 concentrations of 400–800 ppmv may be even slower than the removal of manmade carbon dioxide following cessation of emis-

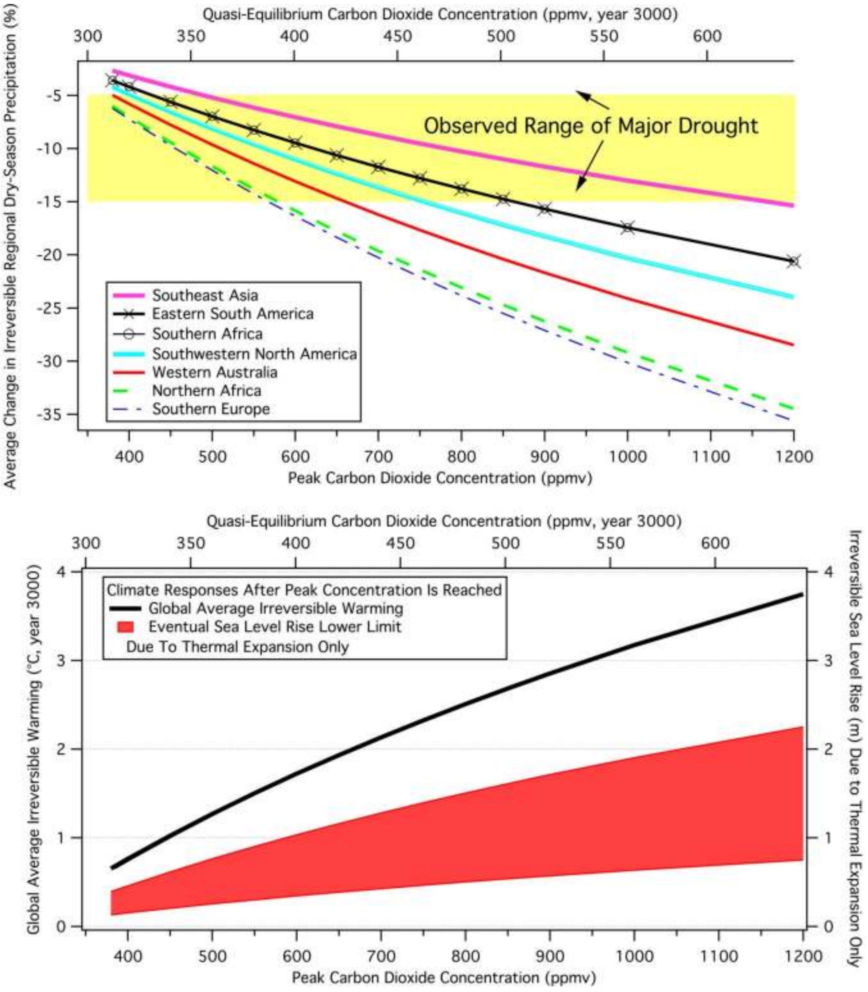

Fig. 4. Illustrative irreversible climate changes as a function of peak carbon dioxide reached. (*Upper*) Best estimate of expected irreversible dry-season precipitation changes for the regions shown in Fig. 3, as a function of the peak carbon dioxide concentration during the 21st century. The quasi-equilibrium CO_2 concentrations shown correspond to 40% remaining in the long term as discussed in the text. The precipitation change per degree is derived for each region as in Fig. 3; see also Fig. S3. The yellow box indicates the range of precipitation change observed during typical major regional droughts such as the ''dust bowl'' in North America (32). (*Lower*) Corresponding irreversible global warming (black line). Also shown is the associated lower limit of irreversible sea level rise (because of thermal expansion only based upon a range of 0.2–0.6 m/°C), from an assessment across available models (5). Smaller values (by ≈30%) for expected warming, precipitation, and thermal sea level rise would be obtained if climate sensitivity is smaller than the best estimate while larger values (by ≈50%) would be expected for the upper end of the estimated likely range of climate sensitivity (49).

sions, so that this loss could contribute less than a meter to irreversible sea level rise even after many thousands of years (44, 45). It is evident that the contribution from the ice sheets could be large in the future, but the dependence upon carbon dioxide levels is extremely uncertain not only over the coming century but also in the millennial time scale.

An assessed range of models suggests that the eventual contribution to sea level rise from thermal expansion of the ocean is expected to be 0.2–0.6 m per degree of global warming (5). Fig. 4 uses this range together with a best estimate for climate sensitivity of 3 °C (5) to estimate lower limits to eventual sea level rise due to thermal expansion alone. Fig. 4 shows that even with zero emissions after reaching a peak concentration, irreversible global average sea level rise of at least 0.4–1.0 m is expected if 21st century CO_2 concentrations exceed 600 ppmv and as much as 1.9 m for a peak CO_2 concentration exceeding ≈1,000 ppmv. Loss of glaciers and small ice caps is relatively well understood and is expected to be largely complete under sustained warming of, for example, 4 °C within ≈500 years (46). For lower values of warming, partial remnants of glaciers might be retained, but this has not been examined in detail for realistic representations of glacier shrinkage and is not quantified here. Complete losses of glaciers and small ice caps have the potential to raise future sea level by ≈0.2–0.7 m (46, 47) in addition to thermal expansion. Further contributions due to partial loss of the great ice sheets of Antarctica and/or Greenland could add several meters or more to these values but for what warming levels and on what time scales are still poorly characterized.

Sea level rise can be expected to affect many coastal regions (48). While sea walls and other adaptation measures might combat some of this sea level rise, Fig. 4 shows that carbon dioxide peak concentrations that could be reached in the future for the conservative lower limit defined by thermal expansion alone can be expected to be associated with substantial irreversible commitments to future changes in the geography of the Earth because many coastal and island features would ultimately become submerged.

Discussion: Some Policy Implications

It is sometimes imagined that slow processes such as climate changes pose small risks, on the basis of the assumption that a choice can always be made to quickly reduce emissions and thereby reverse any harm within a few years or decades. We have shown that this assumption is incorrect for carbon dioxide emissions, because of the longevity of the atmospheric CO$_2$ perturbation and ocean warming. Irreversible climate changes due to carbon dioxide emissions have already taken place, and future carbon dioxide emissions would imply further irreversible effects on the planet, with attendant long legacies for choices made by contemporary society. Discount rates used in some estimates of economic trade-offs assume that more efficient climate mitigation can occur in a future richer world, but neglect the irreversibility shown here. Similarly, understanding of irreversibility reveals limitations in trading of greenhouse gases on the basis of 100-year estimated climate changes (global warming potentials, GWPs), because this metric neglects carbon dioxide's unique long-term effects. In this paper we have quantified how societal decisions regarding carbon dioxide concentrations that have already occurred or could occur in the coming century imply irreversible dangers relating to climate change for some illustrative populations and regions. These and other dangers pose substantial challenges to humanity and nature, with a magnitude that is directly linked to the peak level of carbon dioxide reached.

Materials and Methods

The AOGCM simulation data presented in this paper are part of the World Climate Research Program's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multimodel data set (29) and are available from the Program for Climate Model Diagnosis and Intercomparison (PCMDI) (www-pcmdi.llnl.gov/ipcc/about_ipcc.php), where further information on the AOGCMs can also be obtained. The EMIC used in this study is the Bern2.5CC EMIC described in refs. 7 and 15; it is compared to other models in refs. 5 and 7. It is a coupled climate–carbon cycle model of intermediate complexity that consists of a zonally averaged dynamic ocean model, a 1-layer atmospheric energy–moisture balance model, and interactive representations of the marine and terrestrial carbon cycles.

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Supporting Information

Solomon *et al.* **10.1073/pnas.0812721106**

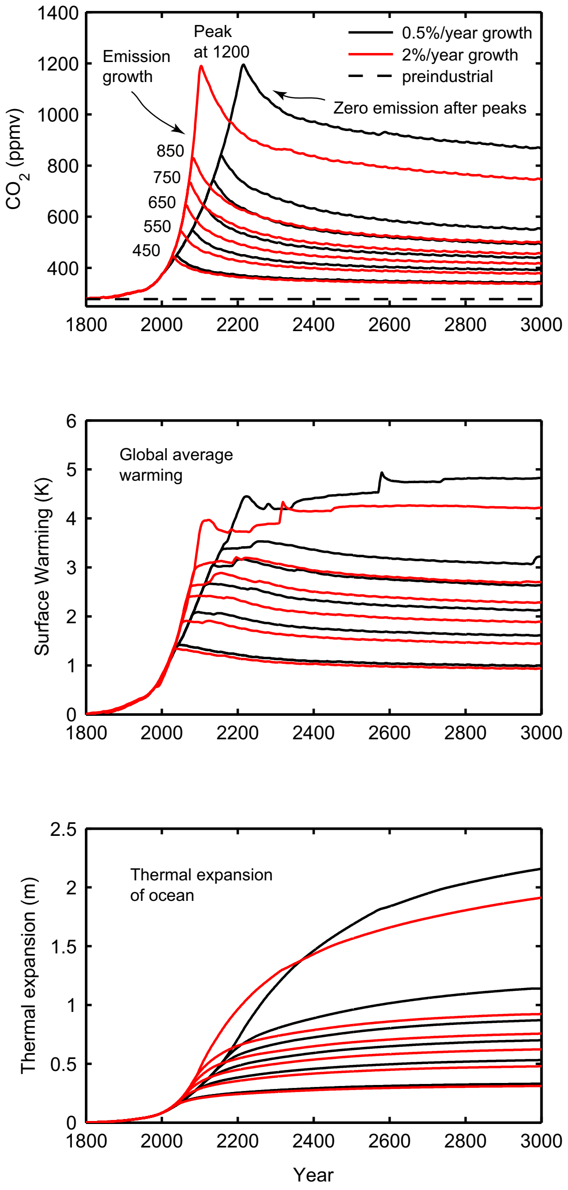

Fig. S1. Carbon dioxide and climate system changes (relative to preindustrial conditions in 1765) from 1 illustrative model, the Bern 2.5CC EMIC, whose results are comparable to the suite of assessed EMICs (1, 2) (see Fig. 1). (*Top*) Falloff of CO_2 concentrations following zero emissions, from peak values of 450, 550, 650, 750, 850, and 1200 ppmv. Black and red lines depict 2 different illustrative future rates of emission growth of 0.5%/year and 2%/year before reaching these peak levels. Total emissions in the 0.5%/year cases are higher than in the corresponding 2%/year cases as the peak CO_2 levels are reached later on, which results in larger climate changes for large perturbations (3). (*Middle*) Globally averaged surface warming (degrees Celsius) for these cases (note that this model has an equilibrium climate sensitivity of 3.2 °C for carbon dioxide doubling). (*Bottom*) Sea level rise (meters) from thermal expansion only (not including glaciers, ice caps, or ice sheets).

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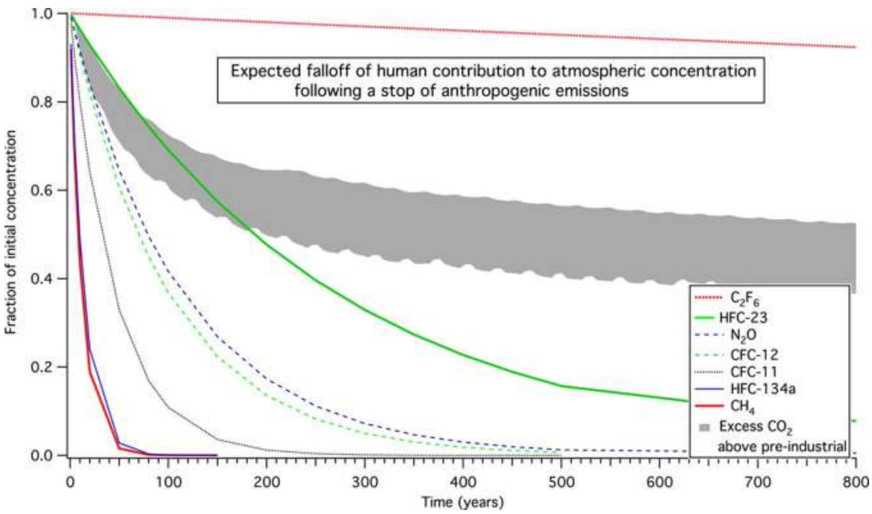

Fig. S2. Typical falloff of concentrations expected for various greenhouse gases, from a peak value following cessation of emissions. The decay of CH_4, N_2O, and halocarbons depends upon their atmospheric lifetimes, which are well represented for realistic cases as single values and are taken from ref. 1. The range of CO_2 decay is based upon calculations with the Bern2.5CC carbon cycle–climate model for the 2%/year rate of increase cases shown in Fig. 1 of the main text covering a broad range of cases in which CO_2 concentrations increase from current concentrations to peak values of 450-1200 ppmv and then emissions are halted. The 31-year variation seen in the carbon dioxide decay is introduced by the climatology used to force the terrestrial biosphere model (2).

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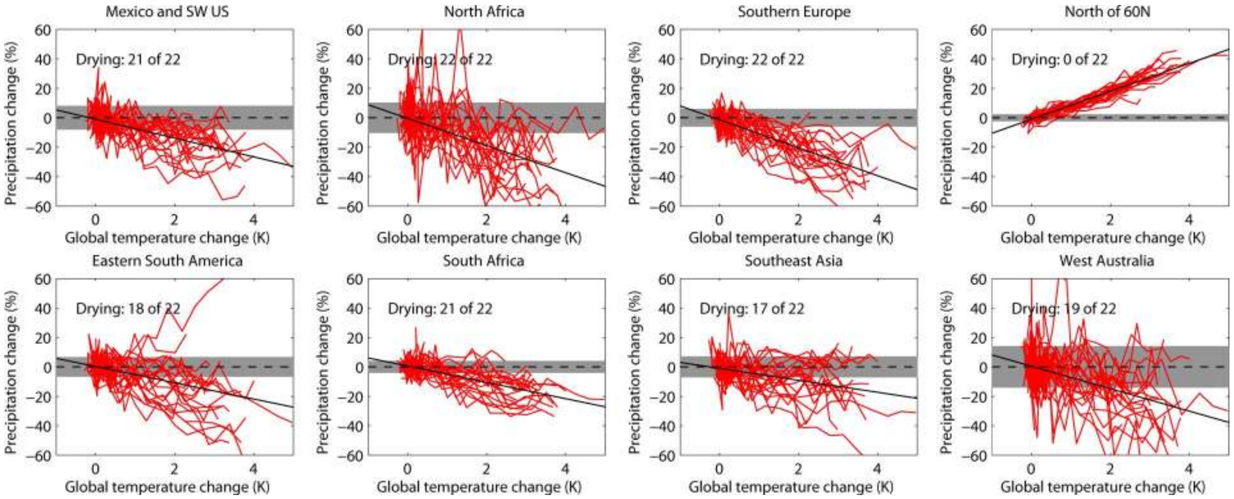

Fig. S3. Relationship between temperature and rainfall averaged over several large regions for a suite of 22 AOGCMs (1, 2) relative to the baseline period of 1900−1950. Two available outlying models that differ greatly from all other AOGCMs were not included, but this choice does not materially affect the results because there are so many models. The model outputs are available at www-pcmdi.llnl.gov/ipcc/about_ipcc.php. Data have been averaged over the regions shown in Fig. 3 (main text) and over a decade, for the 3 driest consecutive months in the baseline period. One ensemble member is used for each model so that all models are equally weighted in a multimodel ensemble. The gray shaded area delimits 1 standard deviation among the models during the baseline period from 1900 to 1950 to estimate the likely uncertainty. The number of models showing drying in each region is indicated.

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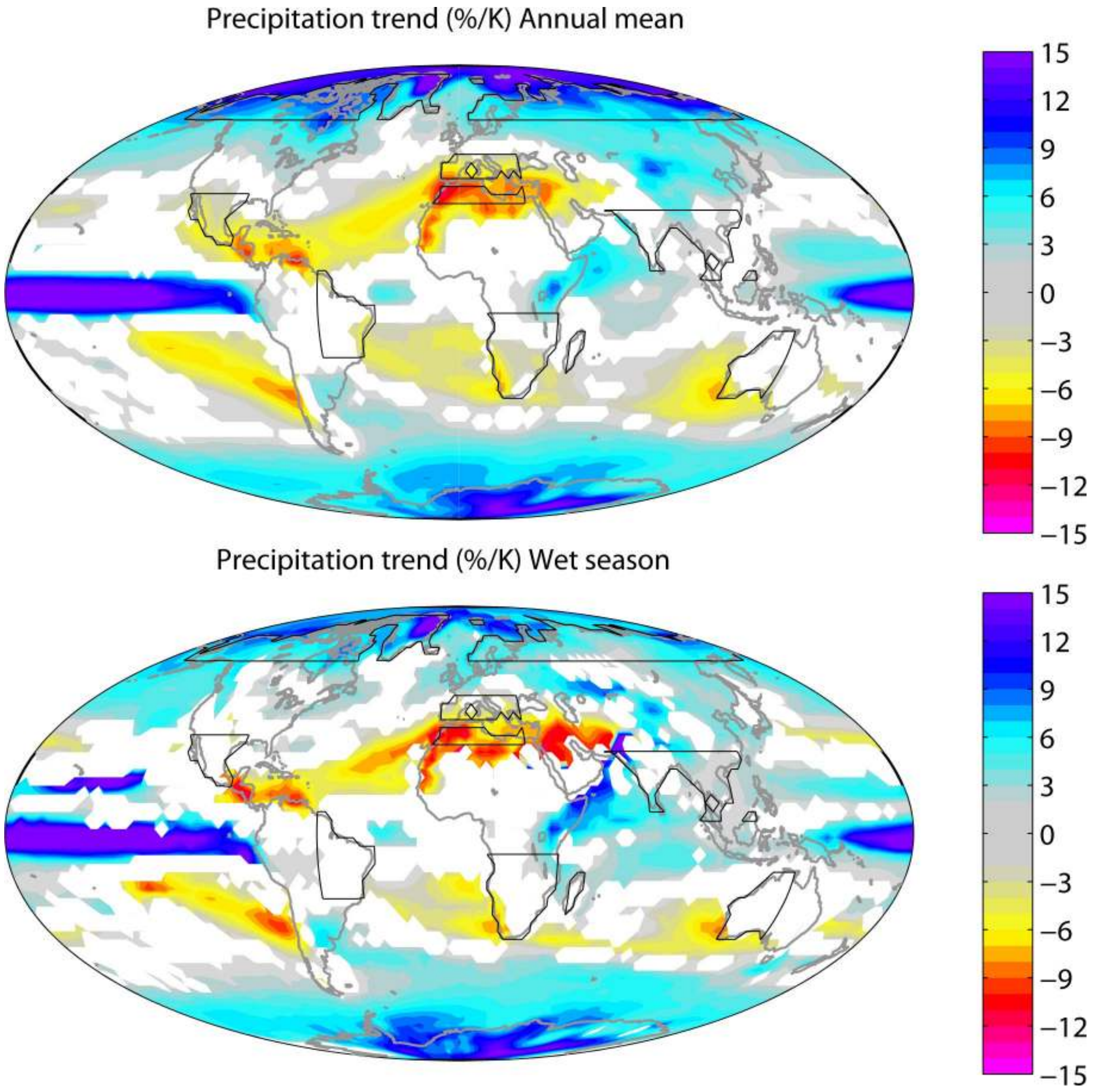

Fig. S4. The same as in Fig. 3 of the main text, but for the annual mean and for the 3 consecutive wettest months. Decadally averaged changes in the global distribution of precipitation per degree of warming are shown (percentage of change in precipitation per degree of warming, relative to 1900–1950 as the baseline period) at each grid point, on the basis of a suite of 22 AOGCMs. White is used where <16 of 22 models agree on the sign of the response, while colors and gray indicate grid points where at least 16 of the 22 models agree.