

Irreversible climate change due to carbon dioxide emissions

Susan Solomon^{a,1}, Gian-Kasper Plattner^b, Reto Knutti^c, and Pierre Friedlingstein^d

^aChemical Sciences Division, Earth System Research Laboratory, National Oceanic and Atmospheric Administration, Boulder, CO 80305; ^bInstitute of Biogeochemistry and Pollutant Dynamics and ^cInstitute for Atmospheric and Climate Science, ETH CH-8092, Zurich, Switzerland; and ^dInstitut 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 à l'Energie Atomique-Saclay, l'Orme des Merisiers, 91191 Gif sur Yvette, France

Contributed by Susan Solomon, December 16, 2008 (sent for review November 12, 2008)

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 CO₂ concentrations exceed 600 ppmv and 0.6–1.9 m for peak CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 multimillennium and longer time scales, geochemical and geological

Author contributions: S.S., G.-K.P., R.K., and P.F. designed research; S.S., G.-K.P., and R.K. performed research; G.-K.P. and R.K. analyzed data; and S.S., G.-K.P., R.K., and P.F. wrote the paper.

The authors declare no conflict of interest.

Freely available online through the PNAS open access option.

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

This article contains supporting information online at www.pnas.org/cgi/content/full/0812721106/DCSupplemental.

© 2009 by The National Academy of Sciences of the USA

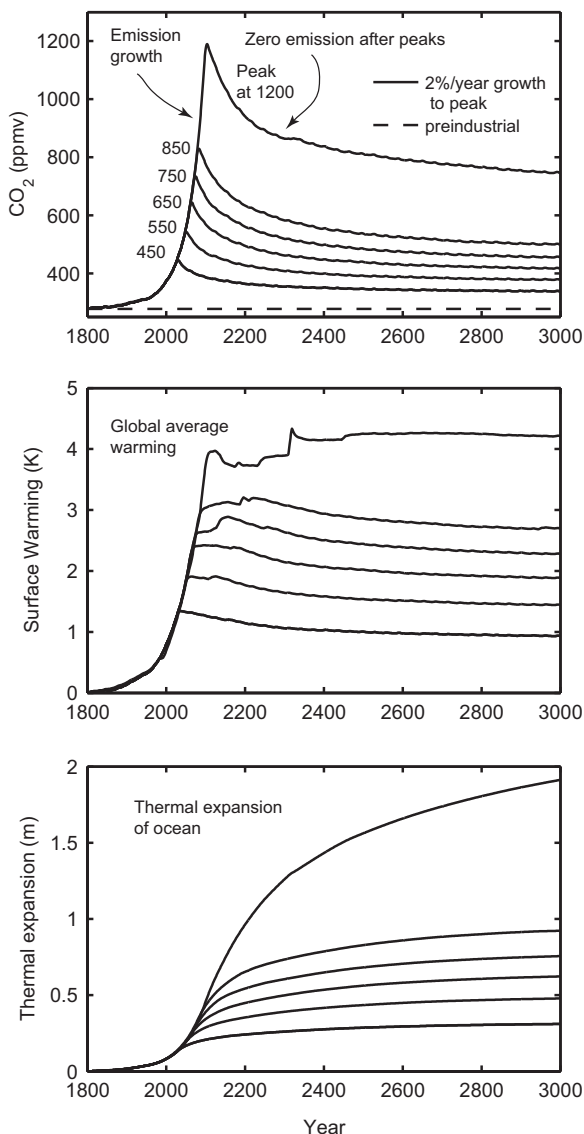


Fig. 1. Carbon dioxide and global mean climate system changes (relative to preindustrial conditions in 1765) from 1 illustrative model, the Bern 2.5CC EMIC, whose results are comparable to the suite of assessed EMICs (5, 7). Climate system responses are shown for a ramp of CO₂ emissions at a rate of 2%/year to peak CO₂ values of 450, 550, 650, 750, 850, and 1200 ppmv, followed by zero emissions. The rate of global fossil fuel CO₂ emission grew at ≈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 CO₂ 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-CO₂ 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 CO₂ is expected to be retained in the atmosphere by the end of the millennium that is surprisingly large: typically ≈40% of the peak concentration enhancement over preindustrial values (≈280 ppmv). This can be easily understood on the basis of the observed instantaneous airborne fraction (AF^{peak}) of ≈50% of anthropogenic carbon emissions retained during their buildup in the atmosphere, together with well-established ocean chemistry and physics that require ≈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, CO₂^{peak} (increase over the preindustrial value CO₂⁰), and the resulting 1,000-year quasi-equilibrium concentration, CO₂^{equi} can be expressed as

$$\text{CO}_2^{\text{peak}} = \text{CO}_2^0 + \text{AF}^{\text{peak}} \cdot \text{EMI} \quad [1]$$

$$\text{CO}_2^{\text{equi}} = \text{CO}_2^0 + \text{AF}^{\text{equi}} \cdot \text{EMI} \quad [2]$$

so that

$$\text{CO}_2^{\text{equi}} - \text{CO}_2^0 = \frac{\text{AF}^{\text{equi}}}{\text{AF}^{\text{peak}}} (\text{CO}_2^{\text{peak}} - \text{CO}_2^0). \quad [3]$$

Given an instantaneous airborne fraction (AF^{peak}) of ≈50% during the period of rising CO₂, and a quasi-equilibrium airborne fraction (AF^{equi}) of 20%, it follows that the quasi-equilibrium enhancement of CO₂ concentration above its preindustrial value is ≈40% of the peak enhancement. For example, if the CO₂ concentration were to peak at 800 ppmv followed by zero emissions, the quasi-equilibrium CO₂ concentration would still be far above the preindustrial value at ≈500 ppmv. Additional carbon cycle feedbacks could reduce the efficiency of the ocean and biosphere to remove the anthropogenic CO₂ and thereby increase these CO₂ values (15, 16). Further, a longer decay time and increased CO₂ concentrations at year 1000 are expected for large total carbon emissions (17).

Irreversible Climate Change: Atmospheric Warming. Global average temperatures increase while CO₂ is increasing and then remain approximately constant (within ≈ ±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 CO₂ concentration decay and reduced cooling through heat loss to the oceans. It arises because long-term carbon dioxide removal

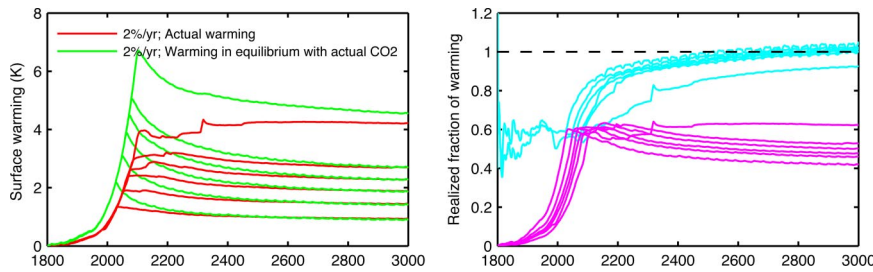


Fig. 2. Comparison between calculated time-dependent surface warming in the Bern2.5CC model and the values that would be expected if temperatures were in equilibrium with respect to the CO₂ enhancements, illustrative of 2%/year emission increases to 450, 550, 650, 750, 850, and 1,200 ppmv as in Fig. 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 CO₂ concentrations), while the magenta lines show the ratio of actual warming to the equilibrium temperature for the peak CO₂ 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 CO₂ 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 $\approx 50\text{--}60\%$ 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 $\approx 40\text{--}60\%$ of the equilibrium warming corresponding to the peak CO₂ 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 ($\approx 15^{\circ}\text{--}40^{\circ}$ 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 $\approx 15\%$) 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 $\approx 10\%$ for 2°C of global mean warming. For comparison, the American “dust

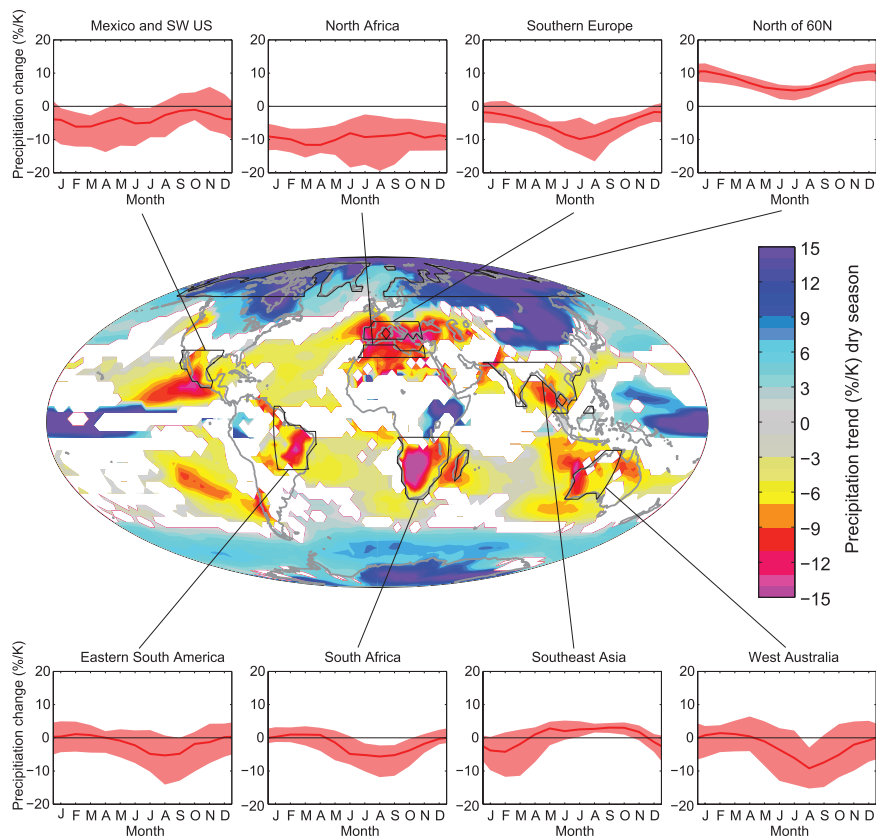


Fig. 3. Expected decadal averaged changes in the global distribution of precipitation per degree of warming (percentage of change in precipitation per degree of warming, relative to 1900–1950 as the baseline period) in the dry season at each grid point, based upon a suite of 22 AOGCMs for a midrange 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 $\pm 1\text{-}\sigma$ likely range (i.e., 2 of 3 chances) across the models.

bowl” was associated with averaged rainfall decreases of $\approx 10\%$ over $\approx 10\text{--}20$ 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 $\approx 40\%$ 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 $\approx 8\text{--}10\%$ 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 $\approx 13\text{--}16\%$ 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-

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 CO₂ 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.

ACKNOWLEDGMENTS. We gratefully acknowledge the modeling groups, the Program for Climate Model Diagnosis and Intercomparison, and the World Climate Research Program's Working Group on Coupled Modeling for their roles in making available the Working Group on Coupled Modeling's Coupled Model Intercomparison Project phase 3 multimodel data set. Support of this data set is provided by the Office of Science, U.S. Department of Energy. We also appreciate helpful comments from 3 reviewers.

- Hansen J, et al. (2007) Dangerous human-made interference with climate: a GISS modelE study. *Atmos Chem Phys* 7:2287–2312.
- Ramanathan V, Feng Y (2008) On avoiding dangerous anthropogenic interference with the climate system: formidable challenges. *Proc Natl Acad Sci USA* 105:14245–14250.
- Schellnhuber HJ (2008) Global warming: Stop worrying, start panicking? *Proc Natl Acad Sci USA* 105:14239–14240.
- Oppenheimer M, Alley RB (2004) The West Antarctic ice sheet and long term climate policy. *Clim Change* 64:1–10.
- Meehl GA, et al. (2007) Global climate projections. *Climate Change 2007: The Physical Science Basis*, eds Solomon S, et al. (Cambridge Univ Press, Cambridge, UK, and New York), pp 747–845.
- Matthews HD, Caldeira K (2008) Stabilizing climate requires near-zero emissions. *Geophys Res Lett* 35:L04705, 10.1029/2007GL032388.
- Plattner GK, et al. (2008) Long-term climate commitments projected with climate-carbon cycle models. *J Clim* 21:2721–2751.
- Parry ML, et al. (2007) *Climate Change 2007: Impacts, Adaptation, and Vulnerability. Contribution of Working Group 2 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge Univ Press, Cambridge, UK, and New York).
- Revelle R, Suess HE (1957) Carbon dioxide exchange between atmosphere and ocean and the question of an increase of atmospheric CO₂ during the past decades. *Tellus* 9:18–27.
- Archer D, Keshgji H, Maier-Reimer E (1997) Multiple timescales for neutralization of fossil fuel CO₂. *Geophys Res Lett* 24:405–408.
- Montenegro A, Brovkin V, Eby M, Archer D, Weaver AJ (2007) Long term fate of anthropogenic carbon. *Geophys Res Lett* 34:L19707, 10.1029/2007GL030905.
- Archer D, Brovkin V (2008) The millennial atmospheric lifetime of anthropogenic CO₂. *Clim Change* 90:283–297, 10.1007/s10584-008-9413-1.
- Raupach MR, et al. (2007) Global and regional drivers of accelerating CO₂ emissions. *Proc Natl Acad Sci USA* 94:10288–10293.
- Forster P, et al. (2007) Changes in atmospheric constituents and in radiative forcing. *Climate Change 2007: The Physical Science Basis*, eds Solomon S, et al. (Cambridge Univ Press, Cambridge, UK, and New York), pp 747–845.
- Joos F, et al. (2001) Global warming feedbacks on terrestrial carbon uptake under the Intergovernmental Panel on Climate Change (IPCC) emission scenarios. *Global Biogeochem Cycles* 15:891–907.
- Schmittner A, Oshlies A, Matthews HD, Galbraith ED (2008) Future changes in climate, ocean circulation, ecosystems, and biogeochemical cycling simulated for a business-as-usual CO₂ emission scenario until year 4000 AD. *Global Biogeochem Cycles* 22:GB1013, 10.1029/2007GB002953.
- Eby M, et al. (2008) Lifetime of anthropogenic climate change: millennial time-scales of potential CO₂ and surface temperature perturbations. *J Clim*, 10.1175/2008JCLI2554.1, in press.
- Flueckiger J, Knutti R, White JWC (2006) Oceanic processes as potential trigger and amplifying mechanisms for Heinrich events. *Paleoceanography* 21:PA2014, doi:10.1029/2005PA001204.
- Stouffer RJ (2004) Time scales of climate response. *J Clim* 17:209–214.
- Allen MR, Ingram WJ (2002) Constraints on future changes in climate and the hydrological cycle. *Nature* 419:224–232.
- Trenberth KE, et al. (2007) Observations: surface and atmospheric climate change. *Climate Change 2007: The Physical Science Basis*, eds Solomon S, et al. (Cambridge Univ Press, Cambridge, UK), pp 747–845.
- Seager R, et al. (2007) Model projections of an imminent transition to a more arid climate in southwestern North America. *Science* 316:1181–1184.
- Zhang X, et al. (2007) Detection of human influence on twentieth-century precipitation trends. *Nature* 448:461–465.
- Gao X, Giorgi F (2008) Increased aridity in the Mediterranean region under greenhouse gas forcing estimated from high resolution simulations with a regional climate model. *Global Planet Change* 62:195–209.
- Burke EJ, Brown SJ, Christidis N (2006) Modelling the recent evolution of global drought and projections for the 21st century with the Hadley Centre climate model. *J Hydrometeorol* 7:1113–1125.
- Held IM, Soden BJ (2006) Robust responses of the hydrological cycle to global warming. *J Clim* 19:5686–5699.
- Manabe S, Stouffer RJ (1980) Sensitivity of a global climate model to an increase of CO₂ concentration in the atmosphere. *J Geophys Res* 85:5529–5554.
- Kutzbach JE, Williams JW, Vavrus SJ (2005) Simulated 21st century changes in regional water balance of the Great Lakes region and links to changes in global temperature and poleward moisture transport. *Geophys Res Lett* L17707, 10.1029/2005GL023506.
- Meehl GA, et al. (2007) The WCRP CMIP3 multi-model dataset: a new era in climate change research. *Bull Am Meteorol Soc* 88:1383–1394.
- Mitchell TD (2003) Pattern scaling: an examination of the accuracy of the technique for describing future climates. *Clim Change* 60:217–242.
- Stouffer RS, Manabe S (1999) Response of a coupled ocean-atmosphere model to increasing atmospheric carbon dioxide: sensitivity to the rate of increase. *J Clim* 12:2224–2237.
- Narisma GT, Foley JA, Licker R, Ramankutty N (2007) Abrupt changes in rainfall during the twentieth century. *Geophys Res Lett* 34:L06710, 10.1029/2006GL028628.
- Robell DB, et al. (2008) Prioritizing climate change adaptation needs for food security in 2030. *Science* 319:607–610.
- Easterling W, et al. (2007) Food, fibre, and forest products. *Climate Change 2007: Impacts, Adaptation, and Vulnerability*, eds Parry ML, et al. (Cambridge Univ Press, Cambridge, UK), pp 273–313.
- Fischlin A, et al. (2007) Ecosystems, their properties, goods and services. *Climate Change 2007: Impacts, Adaptation, and Vulnerability*, eds Parry ML, et al. (Cambridge Univ Press, Cambridge, UK), pp 211–272.
- Williams JW, Jackson ST, Kutzbach JE (2007) Projected distributions of novel and disappearing climates by 2100 AD. *Proc Natl Acad Sci USA* 104:5738–5742.
- Scholze M, Knorr W, Arnell NW, Prentice IC (2006) A climate-change risk analysis for world ecosystems. *Proc Natl Acad Sci USA* 103:13116–13120.
- Westerling AL, Hidalgo HG, Cayan DR, Swetnam TW (2006) Warming and earlier spring increase western US forest wildfire activity. *Science* 313:940–943.
- Bindoff NL, et al. (2007) Observations: oceanic climate change and sea level. *Climate Change 2007: The Physical Science Basis*, eds Solomon S, et al. (Cambridge Univ Press, Cambridge, UK), pp 747–845.
- Rignot E, Kanagaratnam P (2006) Changes in the velocity structure of the Greenland ice sheet. *Science* 311:986–990.
- Joughin I, et al. (2008) Seasonal speedup along the western flank of the Greenland ice sheet. *Science* 320:781–783.
- Pfeffer WT, Harper JT, O'Neil S (2008) Kinematic constraints on glacier contributions to 21st-century sea level rise. *Science* 321:1340–1343.
- Holland DM, Thomas RH, De Young B, Ribergaard MH, Lyberth B (2008) Acceleration of Jakobshavn Isbrae triggered by warm subsurface ocean waters. *Nat Geosci* 1:659–664.
- Charbit S, Paillard D, Ramstein G (2008) Amount of CO₂ emissions irreversibly leading to the total melting of Greenland. *Geophys Res Lett* 35:L12503, 10.1029/2008GL033472.
- Parizek BR, Alley RB (2004) Implications of increased Greenland surface melt under global warming scenarios: ice sheet simulations. *Quat Sci Rev* 23:1013–1027.
- Raper SCB, Braithwaite RJ (2006) Low sea level rise projections from mountain glaciers and icecaps under global warming. *Nature* 439:311–313.
- Lemke P, et al. (2007) Observations: changes in snow, ice, and frozen ground. *Climate Change 2007: The Physical Science Basis*, eds Solomon S, et al. (Cambridge Univ Press, Cambridge, UK), pp 747–845.
- Nicholls RJ, et al. (2007) Coastal systems and low lying areas. *Climate Change 2007: Impacts, Adaptation, and Vulnerability*, eds Parry ML, et al. (Cambridge Univ Press, Cambridge, UK), pp 315–357.
- Knutti R, Hegerl G (2004) The equilibrium sensitivity of the Earth's temperature to radiation changes. *Nat Geosci* 1:735–743.