Irreversible climate change due to carbon dioxide emissions

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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 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.

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 multimillenium and longer time scales, geochemical and geological


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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$_{\text{peak}}$) 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$_{\text{equi}}$), 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$$_{\text{peak}}$ (increase over the preindustrial value CO$_2$$_{\text{preind}}$), and the resulting 1,000-year quasi-equilibrium concentration, CO$_2$$_{\text{equi}}$ can be expressed as

\[
CO_2^{\text{equi}} = CO_2^{\text{preind}} + AF_{\text{equi}} \cdot EMI
\]

so that

\[
CO_2^{\text{equi}} - CO_2^{\text{preind}} = \frac{AF_{\text{equi}}}{AF_{\text{peak}}} (CO_2^{\text{peak}} - CO_2^{\text{preind}}).
\]

Given an instantaneous airborne fraction (AF$_{\text{peak}}$) of $\approx 50\%$ during the period of rising CO$_2$, and a quasi-equilibrium airborne factor (AF$_{\text{equi}}$) 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 $\approx 0.5^\circ$ 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 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
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) 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 ~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 continued warming through year 3000 is maintained at ~40–60% 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 (~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
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).

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 CO₂ concentrations of 400–800 ppmv may be even slower than the removal of manmade carbon dioxide following cessation of emis-

![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 ±1σ likely range (i.e., 2 of 3 chances) across the models.](image-url)
sessions, 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 CO₂ concentrations exceed 600 ppmv and as much as 1.9 m for a peak CO₂ 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
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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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