GEOPHYSICAL RESEARCH LETTERS, VOL. 36, L08703, doi:10.1029/2008GL037074, 2009

How much climate change can be avoided by mitigation?

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Received 18 December 2008; revised 2 March 2009; accepted 18 March 2009; published 21 April 2009.

[1] Avoiding the most serious climate change impacts will require informed policy decisions. This in turn will require information regarding the reduction of greenhouse gas emissions required to stabilize climate in a state not too much warmer than today. A new low emission scenario is simulated in a global climate model to show how some of the impacts from climate change can be averted through mitigation. Compared to a non-intervention reference scenario, emission reductions of about 70% by 2100 are required to prevent roughly half the change in temperature and precipitation that would otherwise occur. By 2100, the resulting stabilized global climate would ensure preservation of considerable Arctic sea ice and permafrost areas. Future heat waves would be 55% less intense, and sea level rise from thermal expansion would be about 57% lower than if a non-mitigation scenario was followed.

Citation: Washington, W. M., R. Knutti, G. A. Meehl, H. Teng, C. Tebaldi, D. Lawrence, L. Buja, and W. G. Strand (2009), How much climate change can be avoided by mitigation?, *Geophys. Res. Lett.*, *36*, L08703, doi:10.1029/2008GL037074.

1. Introduction

[2] Climate change is taking place and mankind is very likely the cause [*Intergovernmental Panel on Climate Change* (*IPCC*), 2007]. The climate models used in the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4) showed global mean warming values for the end of the 21st century as large as 6°C compared to present for the highest emission scenarios. Projected warming was largest over the continents and in the northern polar region. Arctic sea ice extent and thickness was projected to substantially decrease with some models showing a sea ice-free Arctic in summer by 2100 [*IPCC*, 2007] accompanied by decreases in the extent of near surface permafrost [*Lawrence and Slater*, 2005; *Lawrence et al.*, 2008].

[3] Some climate scientists have argued that a warming of 2°C above pre-industrial temperatures (i.e., about 1°C above today) is the threshold for dangerous climate change [*Hansen et al.*, 2007]. The Council of the European Union in 2007 reported that large cuts in emissions are "necessary to ensure that the world stays within the 2°C limit..." [*Council of the European Union*, 2004]. To keep the probability of exceeding a warming of 2°C at a third or less, the atmospheric equivalent CO_2 concentration (i.e., taking into account other greenhouse gases) must be stabilized at 450 ppm or below [*Knutti et al.*, 2005]. The effective CO_2 stabilization level therefore needs to be well below 450 ppm, and current concentrations are already at roughly 380 ppm CO_2. While uncertainties in the carbon cycle lead to uncertainties in the allowable emissions for a 2°C stabilization, it is clear that emission reductions in the 21st century need to be large. There must be similar emission reductions in other greenhouse gases (GHGs) such as methane, nitrous oxide, and CFCs. This is not true for ozone because its changes are largely not caused by direct emissions.

[4] Comprehensive atmosphere ocean general circulation models (AOGCMs) in the IPCC AR4 focused only on non-intervention (non-mitigation) scenarios put together in the IPCC Special Report on Emission Scenarios (SRES) [*Nakicenovic and Swart*, 2000]. Six of the 35 scenarios are used as "illustrative" scenarios or storylines, but no likelihood was attached to any of the scenarios. They are examples of "what-if" cases, not necessarily representative of all possible outcomes. These scenarios assume technological progress (e.g., increase in energy efficiency) and, for example, changes in the energy sector, but only to the extent that these are economically beneficial. However, these scenarios do not include political intervention in the form of mitigation policies to regulate emissions in order to reduce climate change.

[5] To explore the global and regional distributions of future climate change that could be avoided with aggressive mitigation policies such as increased use of conservation, renewables and CO_2 capture and storage, simulations with a comprehensive climate model are performed here with a new low emission mitigation scenario compared to a business-as-usual non-mitigation scenario. These scenarios were prepared by United States Climate Change Science Program (CCSP) scientists as part of a series of assessment reports. The CCSP report 2.1 [*Clarke et al.*, 2007] provides scenarios in which carbon dioxide and other greenhouse gas (GHG) emissions and radiative forcings can be substantially reduced if new energy technologies and strategies are put into place.

[6] Another strategy that has been explored is to apply a combination of mitigation and geoengineering to achieve climate stabilization [e.g., *Wigley*, 2006]. This approach brings into consideration geoengineering as a way to buy more time for implementing a movement away from fossil-based energy. However, geoengineering brings up a number of daunting scientific, engineering, logistical and ethical issues that are beyond the scope of this paper and thus will not be addressed here.

2. Model and Emission Scenarios

[7] We use the DOE Pacific Northwest National Laboratory (PNNL) MiniCAM emission scenarios in the

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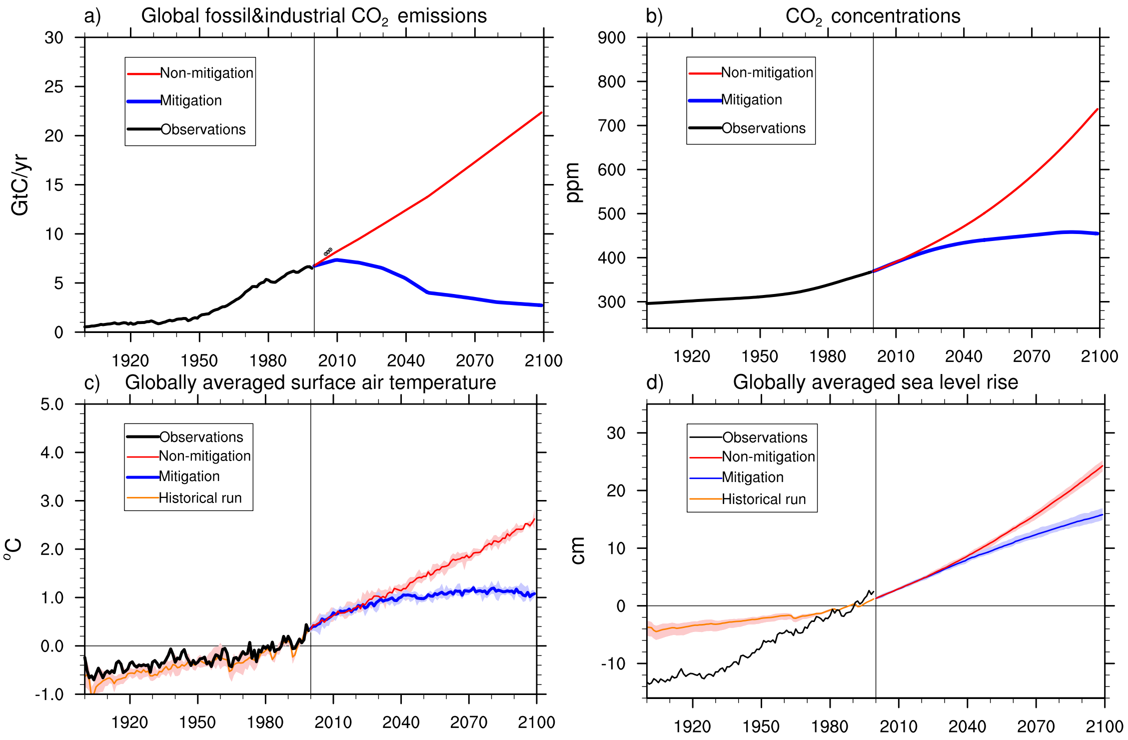

Figure 1. (a) Mitigation (blue) and reference non-mitigation (red) time series of global CO_2 emissions, (b) CO_2 concentrations, (c) globally averaged surface air temperature anomalies calculated from a 1980–1999 reference period, (d) globally averaged sea level rise anomaly (thermal expansion only) calculated from a 1980–1999 reference period. The estimated CO_2 emission and observed concentration data are in black. The mean historical (1900 to 2000) simulation is shown in orange. Note the small dots in Figure 1a above the red curve after the year 2000 show, the 2005–2007 actual CO_2 emissions [*Raupach et al.*, 2007]. The non-mitigation scenario data is less than actual emissions. The range of individual ensemble members is shown in light shading for globally averaged surface temperature and sea level rise. The observed total sea level rise is shown in black in Figure 1d [*Church et al.*, 2001].

simulations in this paper. The other two IAMs [*Clarke et al.*, 2007] give similar CO_2 emissions at 2000 and 2100, however, the Integrated Global Systems Model (IGSM) of the Massachusetts Institute of Technology's Joint Program on the Science gives higher emissions at 2150 and the Model for Evaluating the Regional and Global Effects (MERGE) of GHG reduction policies developed jointly at Stanford University and the Electric Power Research Institute and Policy of Global Change gives less emission at 2050 where they differ about 4 GtC/yr from the PNNL model. The reference non-mitigated CCSP scenario was based upon emission estimates several years before the data were published. Because of large recent emissions in China, the reference level estimates are generally believed to be lower than actual emissions (Figure 1). Thus, the magnitudes of climate change that can be avoided by following the low emission mitigation scenario should be considered conservative estimates. Actual avoided climate change in the mitigation scenario could be greater if business-as-usual emissions continue to increase at rates observed over the past few years.

[8] Two sets of simulations were performed with a state-of-the-art global coupled climate model, the Community Climate System Model (CCSM3) [*Collins et al.*, 2006; *Meehl et al.*, 2005] (see auxiliary material).[1] This model has a relatively low climate sensitivity of 2.7°C for a doubling of CO_2. For future climate, we performed a non-mitigated reference case for comparison to a low emission mitigation scenario (four ensemble members each) which stabilizes atmospheric CO_2 concentration at roughly 450 ppm by the end of year 2100 without an overshoot. CO_2 and other greenhouse gas concentrations are calculated from the emissions specified in the two scenarios by the globally averaged gas-cycle/climate model MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change) that drives a spatial climate-change Scenario Generator (SCENGEN) [*Wigley*, 2008]. It should be noted that our approach does not include an interactive carbon cycle model in the AOGCM, but carbon cycle climate feedbacks are considered in MAGICC when calculating atmospheric CO_2.

3. Results

[9] Atmospheric CO_2 is the dominant anthropogenic greenhouse gas that causes climate change. The 1900 to 2100 time series of CO_2 emissions shows, for the mitigation emissions scenario, a rise over the next decade and then a peak followed by a gradual decline for a net decrease of about 70% of present-day values by the year 2100 (Figure 1a). This corresponds to a stabilized CO_2 concentration of about 450 ppm in 2100 (Figure 1b). The globally averaged surface air temperature increases by about 2.2°C (2080-2099 relative to 1980–1999) in the non-mitigated case, and about

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2008GL037074.

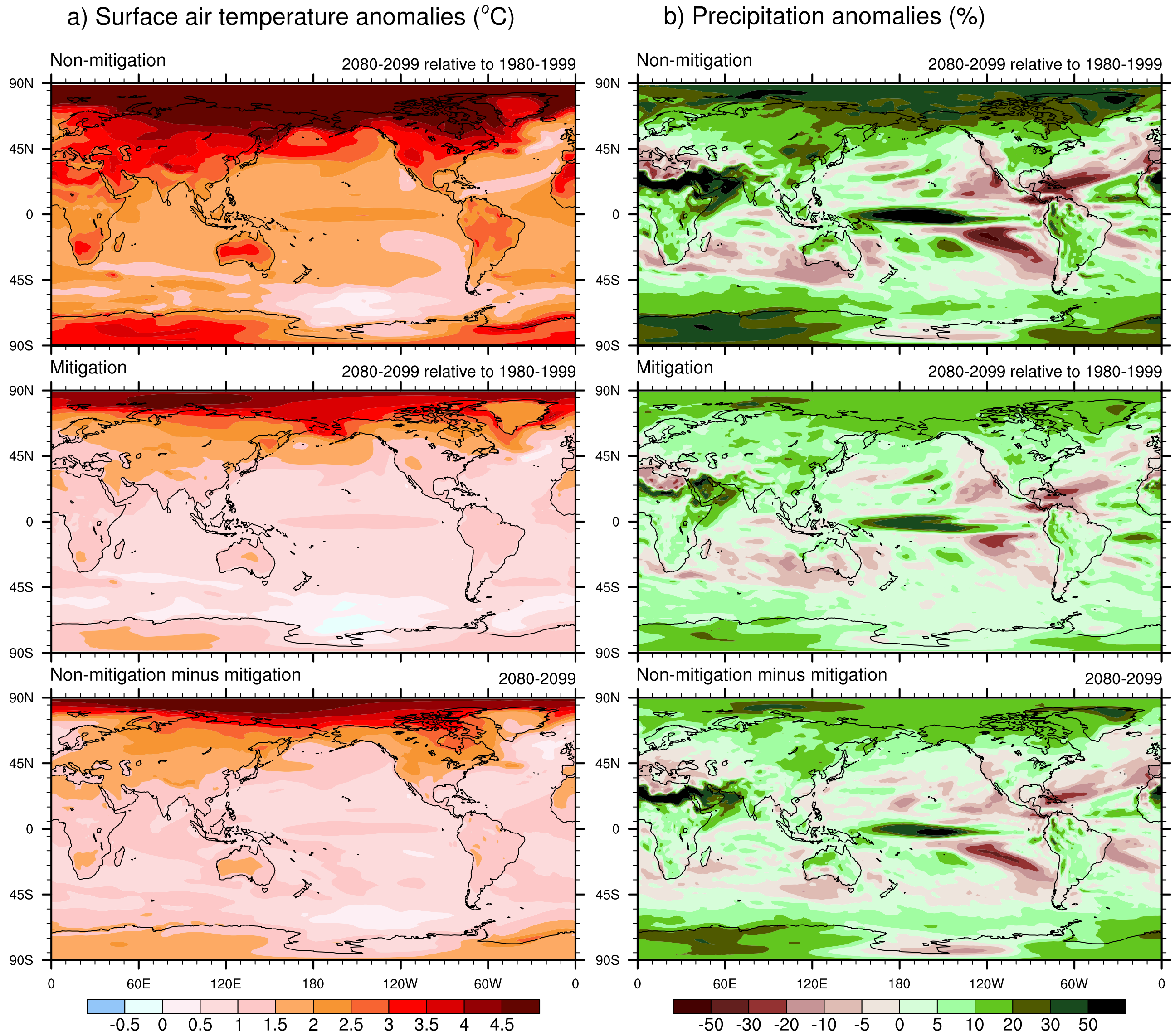

Figure 2. (a) Surface temperature and (b) precipitation changes for the end of the 21st century (ensemble average for years 2080–2099) minus a reference period at the end of the 20th century (ensemble average for years 1980–1999) from 20th-century historical simulations with natural and anthropogenic forcings. (bottom) Non-mitigation minus mitigation to show "warming averted" (Figure 2a) and "% precipitation change averted" (Figure 2b).

0.6°C in the mitigation scenario (Figure 1c). The range of ensemble members is ±0.1°C (other SRES scenarios are shown in the auxiliary material). Thus, by following the mitigation scenario, a potential increase of global temperature of 1.6°C is averted, i.e., in the future we can avoid about twice the warming we have already observed since 1900. The mitigation case also satisfies the target of the Council of the European Union of less than a 2°C rise from preindustrial.

[10] The sea level rise from thermal expansion of the ocean (note that adding glacier and ice sheet melt could more than double this number [*IPCC*, 2007]) is 22 cm in the non-mitigation scenario and 14 cm in the mitigation case. Thus, about 8 cm of the sea level rise that would otherwise occur without mitigation would be averted (Figure 1d). However, by the end of the century the sea level rise continues to increase and does not stabilize in both scenarios due to climate change commitment involving the thermal inertia of the oceans [*Meehl et al.*, 2005]. Recent studies indicate some acceleration of glacier melt over Greenland [e.g., *Joughin et al.*, 2008]. Increased ice sheet calving could lead to a more rapid sea level rise that would continue for several centuries after greenhouse gas concentrations are stabilized irrespective of the emission scenario.

[11] The geographical distribution of warming and precipitation change for the non-mitigated case (Figure 2) shows substantial warming of the annual average of over 5°C in the Arctic region and 2–3°C over the land areas of the Northern hemisphere, while the warming is less over the ocean areas (1–2°C). In the mitigation scenario the warming is roughly half that of the reference case, i.e., 1.0–2.5°C over land and 0.5–2.0°C over the oceans. Therefore, the regional warming that is averted in the mitigation case is roughly 3°C in the Arctic region and 1–2°C over land areas

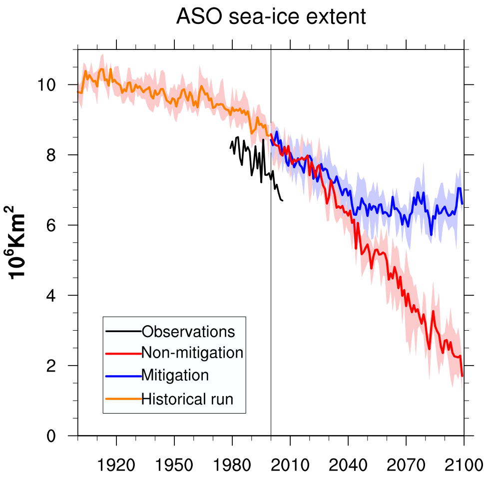

Figure 3. Time series of August, September, and October (ASO) season average Arctic sea ice extent. The dark solid lines are the ensemble means and the shaded areas show the range of ensemble members. The observed sea ice is shown in black, the historical simulation is in orange, the non-mitigation is red and the mitigation is blue. The model shows a systematic positive bias of about 5% compared to the observations but the current trends are similar. In the mitigation simulation the sea ice extent stabilizes in the second half of the 21st century while the non-mitigation simulation decreases markedly in the latter part of the 21st century. Values for just the month of September (not shown) provide a smaller sea ice extent than a three-month average.

(Figure 2). Note that despite a 70% reduction in emissions over the 21st century, there is virtually no cooling. This is consistent with recent results that find similar behavior even for a 1000 yr timescale and a zero emission CO_2 case [*Solomon et al.*, 2009]. The reason is that the decrease in atmospheric CO_2 that would occur in the long term is compensated by the commitment warming.

[12] The non-mitigation case shows up to a 30–50% increase of precipitation in the Arctic region and in the western tropical Pacific, 5–15% increases in the northeast United States and Canada, eastern Asia, South America, and the Sahara. Precipitation decreases by about 30–50% in several areas such as in the eastern Pacific Ocean, the Caribbean, and the southwestern United States. Values for the mitigation case are roughly half that. Thus, the precipitation change that is avoided by following the mitigation scenario is also about half of the non-mitigation case as shown in Figure 2 (bottom).

[13] Arctic sea ice extent for the late summer season average (August, September and October, ASO) for the non-mitigated scenario at the end of the 21st century (Figure 3) has a 76% ice area loss compared to present-day values, whereas the mitigation scenario stabilizes the sea ice extent at about $6.5 \cdot 10^6$ km^2, which is only about a 24% decrease compared to today. Thus, about four million square kilometers of sea ice area are preserved by the end of the century in the mitigated case compared to the non-mitigated case (see Figures S2 and S3).

[14] Large terrestrial ecological changes have been taking place due to the recent summer warming in Alaska, and this warming is amplified by reductions of surface albedo from a more snow-free surface. This in turn causes a rapid shrub and tree expansion in the Arctic region [*Chapin et al.*, 2005]. Minimizing future warming as much as possible with mitigation would limit these changes of ecosystems. Less warming in areas such as the northern Bering Sea would stabilize the presently seen impacts on Arctic marine mammals, sea bird populations, and commercial and subsistence fisheries [*Grebmeier et al.*, 2006]. Additionally, preserving as much summer sea ice area as possible would be critical for the survival of the polar bear population [*Durner et al.*, 2009; *Stirling and Parkinson*, 2006].

[15] The difference in projected changes of near surface permafrost [*Lawrence and Slater*, 2005; *Lawrence et al.*, 2008] between the non-mitigation case (decrease of 70%) and the mitigation case (decrease of 45%) is substantial; with mitigation saving roughly 2.7 million square kilometers of permafrost area by 2100 (see Figure S4). The net result is that the mitigation scenario stabilizes the permafrost extent while the non–mitigated case shows a steady decrease in permafrost. That decrease would be expected to continue well past the end of the century in the unmitigated scenario. If the permafrost extent is stable, that should lessen the concern about additional release of methane stored in the ground that could further amplify global warming.

[16] Extremes also see a lessening of severity in the future mitigation case. For example, the change in the intensity of heat waves [*Meehl and Tebaldi*, 2004] would be 55% less in the mitigation scenario compared to the reference scenario (see Figure S5). The greatest reduction in regional heat wave intensity in the mitigation case occurs over the western United States, Canada, and most of Europe, Russia, and Northern Africa.

[17] Clearly, the impacts of climate change with a mitigation scenario are substantially less than with a non-intervention emission strategy, and the amount of climate change that can be averted with mitigation is considerable. While these scenarios are based on economic models, we do not claim that they are necessarily politically or economically feasible to achieve. As for all scenarios, they should be seen as storylines that illustrate what emission pathways may prevent certain climate changes and associated impacts from happening. The aim is to provide policy relevant information for a range of options, not to advocate particular choices.

[18] **Acknowledgments.** We acknowledge the efforts of scientists at the National Center for Atmospheric Research (NCAR), at several U.S. Department of Energy (DOE) and National Oceanic and Atmospheric Administration Laboratories, and at universities across the United States who contributed to the development of the CCSM3 and who participated in formulating the 20th-century and future climate change simulations. We thank Tom Wigley (NCAR) for providing greenhouse gas concentrations from the CCSP emission data by the use of the MAGICC model. Supercomputer resources were made available through the National Science Foundation (NSF) and DOE. Portions of this study were supported by the Office of Biological and Environmental Research, DOE, as part of its Climate Change Prediction Program (CCPP); and by NCAR. The National Science Foundation sponsors NCAR.

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