The Climate Change Commitment

T. M. L. Wigley

Even if atmospheric composition were fixed today, global-mean temperature and sea level rise would continue due to oceanic thermal inertia. These constant-composition (CC) commitments and their uncertainties are quantified. Constant-emissions (CE) commitments are also considered. The CC warming commitment could exceed 1°C. The CE warming commitment is 2°C to 6°C by the year 2400. For sea level rise, the CC commitment is 10 centimeters per century (range 1 to 30 centimeters per century) and the CE commitment is 25 centimeters per century (7 to 50 centimeters per century). Avoiding these changes requires, eventually, a reduction in emissions to substantially below present levels. For sea level rise, a substantial long-term commitment may be impossible to avoid.

Oceanic thermal inertia causes climate change to lag behind any changes in external forcing and the response to be damped relative to the asymptotic equilibrium response (1–3). Because of this lag or damping effect, and because of the changes in atmospheric composition (and radiative forcing) that have already occurred, the climate system will continue to change for many decades (centuries for sea level) even in the absence of future changes in atmospheric composition. For global-mean temperature, this is referred to as the “unrealized warming” (2), “residual warming” (4), or “committed warming” (5). Here, I use the term “commitment” or, to include sea level rise (6, 7), “climate change commitment.”

The assumption of constant atmospheric composition on which the warming commitment idea is based is clearly unrealistic, even as an extreme case of what might happen in the future. An alternative indicator of the commitment to climate change is to assume that the emissions (rather than concentrations of radiatively important species) will remain constant. This Report investigates the constant-composition (CC) warming and sea level commitments, the constant-emissions (CE) commitments, and the uncertainties in each. Uncertainties arise from uncertainties in the climate sensitivity (2, 4), the rate of ocean heat uptake (2), the magnitude of past forcing, and the ice melt contribution to sea level change.

The usual (or “equilibrium”) CC warming commitment at time $t$ is the difference between the equilibrium warming for forcing at this time ($\Delta T_e$) and the corresponding realized warming ($\Delta T_r$). This is related to the “radiation-imbalance” concept (8, 9). If $\Delta Q$ is the forcing to date, and if $\Delta Q_f$ is the forcing that gives an equilibrium warming of $\Delta T_e$, then the radiation imbalance is $\Delta Q - \Delta Q_f$ ($\Delta Q - \Delta Q_f$ is approximately equal to the flux of heat into the ocean (9)). Hence

$$\Delta T_e - \Delta T_r = (\Delta Q - \Delta Q_f) \Delta T_d$$

where $\Delta Q_d$ is the radiative forcing for a CO$_2$ doubling (about 3.7 W/m$^2$) and $\Delta T_d$ is the corresponding equilibrium global-mean warming. A central estimate of $\Delta Q_f$ accounting for both natural and anthropogenic forcings is about 1.7 W/m$^2$, whereas $\Delta T_d$ is about

References and Notes

23. The orientation is not related to the tip scanning direction. Change of the orientation of the mica substrate does not change the growth of the crystals or their orientation with respect to each other and the mica.
24. X. Liu et al., data not shown.
26. Materials and methods are available as supporting material on Science Online.
31. Supported by the Nanoscale Science and Engineering Initiative of the NSF under NSF Award No. EEC-0118025, the NIH through Award No. GM62109-02, and a Director’s Pioneer Award to C.A.M., the Institute for BioNanotechnology in Medicine, Baxter HealthCare Corp, and the Air Force Office of Scientific Research (AFOSR) through a Multidisciplinary University Research Initiative (MURI) Award.

Supported Online Material

www.sciencemag.org/cgi/content/full/307/5716/1763/DC1
Materials and Methods
Fig. S1 to S5
Table S1
References
6 January 2005; accepted 3 February 2005
10.1126/science.1109487

National Center for Atmospheric Research, Boulder, CO 80307, USA. E-mail: wigley@cdg.ucar.edu
0.7°C. Given $\Delta T_2 = 2.6^\circ$C (10), a central value for the current equilibrium warming commitment is about 0.5°C, with a corresponding radiation-imbalance estimate of 0.7 W/m². These results are in accord with other estimates in the literature, but uncertainties are large.

Because it would take an infinite time for the unrealized warming to appear, a more useful definition makes the unrealized warming a time-dependent quantity, namely, the evolving changes in global-mean temperature that would result if atmospheric composition were kept constant at its present state (4). This is the definition I use here. Temperatures under this new definition tend asymptotically to the previous equilibrium commitment definition. The new definition can be applied equally to the CC and CE commitments and can be used for both temperature and sea level.

To quantify the changes in global-mean temperature and sea level that would occur if either atmospheric composition or the emissions of radiatively important gases were kept constant at today’s levels (the year 2000 is used to define “today”), I used the simple coupled gas-cycle/climate model MAGICC (10–12). MAGICC has been calibrated against a range of coupled atmosphere/ocean general-circulation models (13, 14) and was used in the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report (TAR) and earlier IPCC reports to produce the standard projections of global-mean temperature and sea level change. For access to MAGICC, see (15).

For sea level rise commitments, a change has been made in the way the melt contribution from land-based Glaciers and Small Ice Caps (GSICs) is calculated. In the TAR, the GSIC formula was only meant to be applied through the year 2100 (I project to the year 2400 here). Because of an empirical area-correction term used in the TAR (16), GSIC results are unrealistic beyond 2100, and the correction term imposes an artificial melt maximum (17). The modified formulation (17) matches the TAR results well through the year 2100 and then tends asymptotically to the initially available GSIC ice mass (taken as 40-cm sea level equivalent).

The other TAR sea level rise terms are (16) thermal expansion (a direct output of the climate model), mass-balance changes for the Greenland and Antarctic ice sheets, long-time-scale changes in these ice masses due to past climate change, deposition of sediments on the ocean floor, and runoff from the thawing of permafrost. In the TAR formulation, the last three components (referred to here as “unforced contributions”) are independent of past forcings. To quantify nonexpansion uncertainties, I used methods employed in the TAR.

For the CC and CE temperature commitments, the primary sources of uncertainty are past radiative forcing, the climate sensitivity, and the rate of ocean heat uptake. For past forcing, I considered the effect of natural forcings from solar irradiance changes (18) and volcanic eruptions (19), and uncertainties in aerosol forcing. For climate sensitivity, I used a central value of $\Delta T_2 = 2.6^\circ$C and a range of 1.5° to 4.5°C, approximately equal to the 90% confidence interval (CI) (10). For ocean mixing, I used vertical diffusivities ($K_z$) of 1.3, 2.3, and 4.1 cm²/s, also representing the 90% CI and median values (10).

A breakdown of the natural and anthropogenic components of the CC commitment, together with uncertainties arising from ocean mixing ($K_z$) uncertainties, is given in table S1. Past natural forcing (inclusion of which is the default case here) has a marked effect. The natural forcing component is surprisingly large, 64% of the total commitment in 2050, reducing to 52% by 2400. The effect of ocean mixing uncertainties is small, at most 7%.

Overall results and uncertainties associated with aerosol forcing and the climate sensitivity are shown in Fig. 1 (CC case) and Fig. 2 (CE case). Aerosol forcing is characterized by the forcing in 1990. The central values (and uncertainty ranges) are those used for global-mean warming projections in the TAR (10, 13): –0.4 W/m² (–0.3 W/m² to –0.5 W/m²) and –0.8 W/m² (–0.4 W/m² to –1.2 W/m²) for direct and indirect sulfate forcing, and –0.1 W/m² (–0.2 W/m² to +0.1 W/m²) for the sum of biomass and fossil and organic carbonaceous aerosols. The central value for total aerosol forcing is –1.3 W/m² (range, –0.6 W/m² to –1.9 W/m²). Results depend primarily on the total aerosol forcing rather than the specific breakdown into different forcing categories. Extreme combinations, such as high climate sensitivity with low aerosol forcing, have very low probability (20).

In the CC case (Fig. 1), both climate sensitivity and aerosol forcing uncertainties are of similar importance. The eventual (equilibrium) commitment could be larger than 1°C (for high sensitivity and low aerosol forcing; low aerosol forcing means a higher value for past total forcing). This result is consistent with Wetherald et al. (5) because the Geophysical Fluid Dynamics Laboratory (GFDL) model used by these authors has a high sensitivity (4°C) (14). At the other extreme, the eventual commitment could be less than 0.2°C (for low sensitivity, virtually independent of the magnitude of aerosol forcing).

**Fig. 1.** CC warming commitment (constant concentrations after 2000) for different climate sensitivities and aerosol forcing levels (L, M, and H on the right of the figure indicate low, mid-, and high magnitudes for aerosol forcing, respectively). Values for the central sensitivity value (2.6°C equilibrium warming for a CO₂ doubling) are shown in red.

**Fig. 2.** CE warming commitment (CEs after 2000) for different climate sensitivities and aerosol forcing levels (L, M, and H on the right of the figure indicate low, mid-, and high magnitudes for aerosol forcing, respectively).
Warming commitments for the CE case are much higher and do not tend to any asymptotic limit even on a time scale of millennia (largely because, at CE, CO₂ concentrations continue to grow for many centuries). Climate sensitivity uncertainties are the dominant source of commitment uncertainty. By 2400, the warming ranges from about 2°C (for low sensitivity) to almost 6°C (high sensitivity). The clear message here is that, if we are to avoid future warming of this magnitude, emissions of radiatively active gases will have to be reduced to substantially below present levels.

For the sea level rise commitment results, we have an additional source of uncertainty in the ice melt and unforced contributions to sea level rise. Table S2 shows uncertainties in the ice melt and unforced contributions to sea level rise (40% in the central commitment estimate (mid-aerosol forcing, high melt), the rate of rise is almost 30 cm/century (26% due to unforced effects). At the extreme high end (high sensitivity, low aerosol forcing, high melt), the rate of rise is much higher and do not tend to any asymptotic limit even on a time scale of millennia (largely because, at CE, CO₂ concentrations continue to grow for many centuries). Climate sensitivity uncertainties are the dominant source of commitment uncertainty. By 2400, the warming ranges from about 2°C (for low sensitivity) to almost 6°C (high sensitivity). The clear message here is that, if we are to avoid future warming of this magnitude, emissions of radiatively active gases will have to be reduced to substantially below present levels.

For the sea level rise commitment results, we have an additional source of uncertainty in the ice melt and unforced contributions to sea level rise. Table S2 shows uncertainties in the ice melt and unforced contributions to sea level rise (40% in the central commitment estimate (mid-aerosol forcing, high melt), the rate of rise is almost 30 cm/century (26% due to unforced effects). At the extreme high end (high sensitivity, low aerosol forcing, high melt), the rate of rise is much higher and do not tend to any asymptotic limit even on a time scale of millennia (largely because, at CE, CO₂ concentrations continue to grow for many centuries). Climate sensitivity uncertainties are the dominant source of commitment uncertainty. By 2400, the warming ranges from about 2°C (for low sensitivity) to almost 6°C (high sensitivity). The clear message here is that, if we are to avoid future warming of this magnitude, emissions of radiatively active gases will have to be reduced to substantially below present levels.

For the sea level rise commitment results, we have an additional source of uncertainty in the ice melt and unforced contributions to sea level rise. Table S2 shows uncertainties in the ice melt and unforced contributions to sea level rise (40% in the central commitment estimate (mid-aerosol forcing, high melt), the rate of rise is almost 30 cm/century (26% due to unforced effects). At the extreme high end (high sensitivity, low aerosol forcing, high melt), the rate of rise is much higher and do not tend to any asymptotic limit even on a time scale of millennia (largely because, at CE, CO₂ concentrations continue to grow for many centuries). Climate sensitivity uncertainties are the dominant source of commitment uncertainty. By 2400, the warming ranges from about 2°C (for low sensitivity) to almost 6°C (high sensitivity). The clear message here is that, if we are to avoid future warming of this magnitude, emissions of radiatively active gases will have to be reduced to substantially below present levels.

For the sea level rise commitment results, we have an additional source of uncertainty in the ice melt and unforced contributions to sea level rise. Table S2 shows uncertainties in the ice melt and unforced contributions to sea level rise (40% in the central commitment estimate (mid-aerosol forcing, high melt), the rate of rise is almost 30 cm/century (26% due to unforced effects). At the extreme high end (high sensitivity, low aerosol forcing, high melt), the rate of rise is much higher and do not tend to any asymptotic limit even on a time scale of millennia (largely because, at CE, CO₂ concentrations continue to grow for many centuries). Climate sensitivity uncertainties are the dominant source of commitment uncertainty. By 2400, the warming ranges from about 2°C (for low sensitivity) to almost 6°C (high sensitivity). The clear message here is that, if we are to avoid future warming of this magnitude, emissions of radiatively active gases will have to be reduced to substantially below present levels.

For the sea level rise commitment results, we have an additional source of uncertainty in the ice melt and unforced contributions to sea level rise. Table S2 shows uncertainties in the ice melt and unforced contributions to sea level rise (40% in the central commitment estimate (mid-aerosol forcing, high melt), the rate of rise is almost 30 cm/century (26% due to unforced effects). At the extreme high end (high sensitivity, low aerosol forcing, high melt), the rate of rise is much higher and do not tend to any asymptotic limit even on a time scale of millennia (largely because, at CE, CO₂ concentrations continue to grow for many centuries). Climate sensitivity uncertainties are the dominant source of commitment uncertainty. By 2400, the warming ranges from about 2°C (for low sensitivity) to almost 6°C (high sensitivity). The clear message here is that, if we are to avoid future warming of this magnitude, emissions of radiatively active gases will have to be reduced to substantially below present levels.

For the sea level rise commitment results, we have an additional source of uncertainty in the ice melt and unforced contributions to sea level rise. Table S2 shows uncertainties in the ice melt and unforced contributions to sea level rise (40% in the central commitment estimate (mid-aerosol forcing, high melt), the rate of rise is almost 30 cm/century (26% due to unforced effects). At the extreme high end (high sensitivity, low aerosol forcing, high melt), the rate of rise is much higher and do not tend to any asymptotic limit even on a time scale of millennia (largely because, at CE, CO₂ concentrations continue to grow for many centuries). Climate sensitivity uncertainties are the dominant source of commitment uncertainty. By 2400, the warming ranges from about 2°C (for low sensitivity) to almost 6°C (high sensitivity). The clear message here is that, if we are to avoid future warming of this magnitude, emissions of radiatively active gases will have to be reduced to substantially below present levels.

For the sea level rise commitment results, we have an additional source of uncertainty in the ice melt and unforced contributions to sea level rise. Table S2 shows uncertainties in the ice melt and unforced contributions to sea level rise (40% in the central commitment estimate (mid-aerosol forcing, high melt), the rate of rise is almost 30 cm/century (26% due to unforced effects). At the extreme high end (high sensitivity, low aerosol forcing, high melt), the rate of rise is much higher and do not tend to any asymptotic limit even on a time scale of millennia (largely because, at CE, CO₂ concentrations continue to grow for many centuries). Climate sensitivity uncertainties are the dominant source of commitment uncertainty. By 2400, the warming ranges from about 2°C (for low sensitivity) to almost 6°C (high sensitivity). The clear message here is that, if we are to avoid future warming of this magnitude, emissions of radiatively active gases will have to be reduced to substantially below present levels.
central case). For the CE commitment, sea level rises at about 25 cm/century (uncertainty range, 7 to more than 50 cm/century). The fractions arising from unforced contributions to sea level rise are less than those in the CC case.

The CE results reinforce the common knowledge that, in order to stabilize global-mean temperatures, we eventually need to reduce emissions of greenhouse gases to well below present levels (21). The CC results are potentially more alarming, because they are based on a future scenario that is clearly impossible to achieve and so represent an extreme lower bound to climate change over the next few centuries. For temperature, they show that the inertia of the climate system alone will guarantee continued warming and that this warming may eventually exceed 1°C. For sea level, a continued rise of about 10 cm/century for many centuries is the best estimate. Although such a slow rate may allow many coastal communities to adapt, profound-long-term impacts on low-lying island communities and on vulnerable ecosystems (such as coral reefs) seem inevitable.

References and Notes
15. Materials and methods are available as supporting material on Science Online.
20. This is a sensitivity study and not a probabilistic analysis. Simplistically, if the high climate sensitivity and low forcing extremes are independent and each has a probability of exceedance of 0.05, the probability of both being exceeded is 0.0025. Further constraints may be placed by comparing model simulations with observed climate changes over the past century (22).
23. Supported in part by the U.S. Environmental Protection Agency under contract no. GS-10F-0299K to Stratus Consulting and by NOAA under grant NAB7GP0105. Opinions, findings, or conclusions expressed are those of the author and do not necessarily reflect the views of the funding organization. The National Center for Atmospheric Research is supported by the NSF.

Supporting Online Material
www.sciencemag.org/cgi/content/full/307/5716/1766/DC1
Materials and Methods
Tables 51 and 52
11 August 2004; accepted 10 January 2005
10.1126/science.1103934

How Much More Global Warming and Sea Level Rise?


Two global coupled climate models show that even if the concentrations of greenhouse gases in the atmosphere had been stabilized in the year 2000, we are already committed to further global warming of about another half degree and an additional 320% sea level rise caused by thermal expansion by the end of the 21st century. Projected weakening of the meridional overturning circulation in the North Atlantic Ocean does not lead to a net cooling in Europe. At any given point in time, even if concentrations are stabilized, there is a commitment to future climate changes that will be greater than those we have already observed.

Increases of greenhouse gases (GHGs) in the atmosphere produce a positive radiative forcing of the climate system and a consequent warming of surface temperatures and rising sea level caused by thermal expansion of the warmer seawater, in addition to the contribution from melting glaciers and ice sheets (1, 2). If concentrations of GHGs could be stabilized at some level, the thermal inertia of the climate system would still result in further increases in temperatures, and sea level would continue to rise (2–9). We performed multimember ensemble simulations with two global coupled three-dimensional climate models to quantify how much more global warming and sea level rise (from thermal expansion) we could experience under several different scenarios.

The Parallel Climate Model (PCM) has been used extensively for climate change experiments (10–15). This model has a relatively low climate sensitivity as compared to other models, with an equilibrium climate sensitivity of 2.1°C and a transient climate response (TCR) (the globally averaged surface air temperature change at the time of CO2 doubling in a 1% CO2 increase experiment) of 1.3°C. The former is indicative of likely atmospheric feedbacks in the model, and the latter includes ocean heat uptake and provides an indication of the transient response of the coupled climate system (6, 12). A second global coupled climate model is the newly developed Community Climate Model version 3 (CCSM3), with higher horizontal resolution (atmospheric gridpoints roughly every 1.4° as compared to the PCM, with gridpoints about every 2.8°) and improved parameterizations in all components of atmosphere, ocean, sea ice, and land surface (16). The CCSM3 has somewhat higher sensitivity, with an equilibrium climate sensitivity of 2.7°C and TCR of 1.5°C. Both models have about 1° ocean resolution (0.5° in the equatorial tropics), with dynamical sea ice and land surface schemes. These models were run for four- and eight-member ensembles for the PCM and CCSM3, respectively, for each scenario (except for five members for A2 in CCSM3). The 20th-century simulations for both models include time-evolving changes in forcing from solar, volcanoes, GHGs, stratospheric and tropospheric ozone, and the direct effect of sulfate aerosols (14, 17). Additionally, the CCSM3 includes black carbon distributions scaled by population over the 20th century, with those values scaled by sulfur dioxide emissions for the rest of the future climate simulations. The CCSM3 also uses a different solar forcing data set for the 20th century (18). These 20th-century forcing differences between CCSM3 and PCM are not thought to cause large differences in response in the climate change simulations beyond the year 2000.

The warming in both the PCM and CCSM3 is close to the observed value of about 0.6°C for the 20th century (19), with PCM warming 0.6°C and CCSM3 warming 0.7°C (averaged over the period 1980–1999 in relation to 1890–1919). Sea level rises are 3 to 5 cm, respectively, over the 20th century as com-

*To whom correspondence should be addressed. E-mail: meehl@ncar.ucar.edu