tral 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.

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Supporting Online Material

www.sciencemag.org/cgi/content/full/307/5716/1766/DC1
Materials and Methods
Tables S1 and S2

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How Much More Global Warming and Sea Level Rise?

Gerald A. Meehl,* Warren M. Washington, William D. Collins, Julie M. Arblaster, Aixue Hu, Lawrence E. Buja, Warren G. Strand, Haiyan Teng

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.

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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 CO_2 doubling in a 1% CO_2 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 System 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, tropospheric and stratospheric 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° (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 compared to the observed estimate of 15 to 20 cm. This lower value from the models is consistent with the part of 20th-century sea level rise thought to be caused by thermal expansion (*20*, *21*), because as the ocean warms, seawater expands and sea level rises. Neither model includes contributions to sea level rise due to ice sheet or glacier melting. Partly because of this, the sea level rise calculations for the 20th century from the models are probably at least a factor of 3 too small (*20*, *21*). Therefore, the results here should be considered to be the minimum values of sea level rise. Contributions from future ice sheet and glacier melting could perhaps at least double the projected sea level rise produced by thermal expansion (*1*).

Atmospheric CO_2 is the dominant anthropogenic GHG (*22*), and its time evolution can be used to illustrate the various scenarios (Fig. 1A). The three Special Report for Emissions Scenarios (SRES) show low (B1), medium (A1B), and high (A2) increases of CO_2 over the course of the 21st century. Three stabilization experiments were performed: one with concentrations of all constituents held constant at year 2000 values and two (B1 and A1B) with concentrations held constant at year 2100 values. Although these are idealized stabilization experiments, it would take a significant reduction of emissions below 1990 values within a few decades and within about a century to achieve stabilized concentrations in B1 and A1B, respectively (*23*).

Even if we could have stopped any further increases in all atmospheric constituents as of the year 2000, the PCM and CCSM3 indicate that we are already committed to 0.4° and 0.6°C, respectively, more global warming by the year 2100 as compared to the 0.6°C of warming observed at the end of the 20th century (Table 1 and Fig. 1B). (The range of the ensembles for the climate model temperature anomalies here and to follow is about ±0.1°C.) But we are already committed to proportionately much more sea level rise from thermal expansion (Fig. 1C).

At the end of the 21st century, as compared to the end of the 20th century (1980–1999 base period), warming in the low-estimate climate change scenario (SRES B1) is 1.1° and 1.5°C in the two models (Table 1 and Fig. 1B), with sea level rising to 13 and 18 cm above year 1999 levels. The spread among the ensembles for sea level in all cases amounts to less than ±0.3 cm. A medium-range scenario (SRES A1B) produces a warming at the end of the 21st century of 1.9° and 2.6°C, with about 18 and 25 cm of sea level rise in the two models. For the high-estimate scenario (A2), warming at 2100 is about 2.2° and 3.5°C, and sea level rise is 19 and 30 cm. The range of transient temperature response in the two models for the 20th century through the mid-21st century is considerably less than the range in their equilibrium climate sensitivities (Table 1) due in part to less than doubled CO_2 forcing as well as ocean heat uptake characteristics (*24*). Thus, our confidence in model simulations of 20th-century climate change and projections for much of the 21st century (as represented by the range

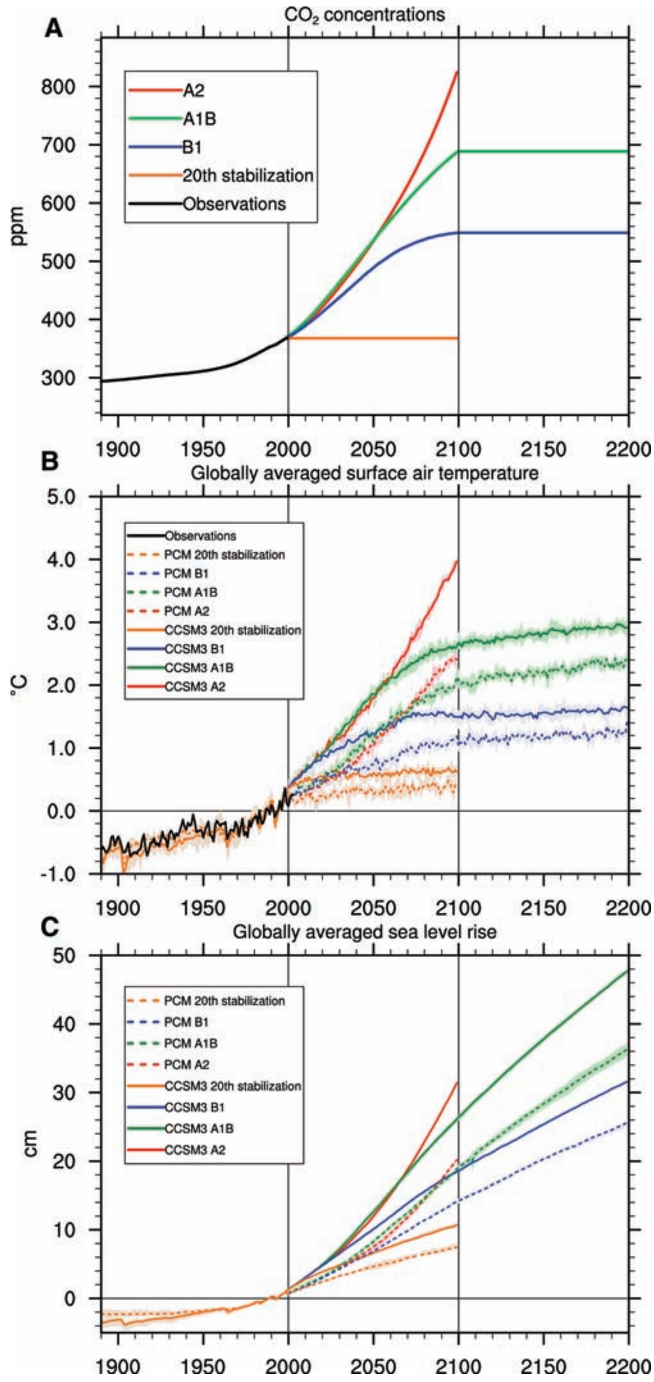

Fig. 1. (**A**) Time series of CO_2 concentrations for the various scenarios. (**B**) Time series of globally averaged surface air temperatures from the PCM and CCSM3. (**C**) Same as (B), except that sea level rise comes from thermal expansion only. In (C), the control drift is first subtracted from each experiment, and then in (B) and (C), the base period for calculating anomalies is 1980–1999. Solid lines are ensemble means, and shading indicates the range of ensemble members. Line identifiers for the various scenarios and the two models are given in each panel.

Table 1. Globally averaged surface temperature differences (in °C) comparing equilibrium climate sensitivity from the two models with simulated warming for the 20th century, mid–21st century, and late 21st century for the different experiments. Midcentury differences are calculated for 2041–2060 minus 1980–1999, and late century differences are for 2080–2099 minus 1980–1999. A2 at 2100 has more than double present-day CO_2 amounts (Fig. 1A).

Model	Equilibrium sensitivity	20th century	2050 stabilized	2050 B1	2050 A1B	2050 A2	2100 stabilized	2100 B1	2100 A1B	2100 A2
PCM	2.1	0.6	0.3	0.7	1.2	1.1	0.4	1.1	1.9	2.2
CCSM3	2.7	0.7	0.6	1.2	1.9	1.8	0.6	1.5	2.6	3.5

in the transient response of the models) is considerably better than that represented by the larger uncertainty range of the equilibrium climate sensitivity among the models.

If concentrations of all GHGs and other atmospheric constituents in these simulations are held fixed at year 2100 values, we would be committed to an additional warming by the year 2200 for B1 of about 0.1° to 0.3°C for the models (Fig. 1B). This small warming commitment is related to the fact that CO_2 concentrations had already started to stabilize at about 2050 in this scenario (Fig. 1A). But even for this small warming commitment in B1, there is almost double the sea level rise seen over the course of the 21st century by 2200, or an additional 12 and 13 cm (Fig. 1C). For A1B, about 0.3°C of additional warming occurs by 2200, but again there is roughly a doubling of 21st-century sea level rise by the year 2200, or an additional 17 and 21 cm. By 2300 (not shown), with concentrations still held at year 2100 values, there would be less than another 0.1°C of warming in either scenario, but yet again about another doubling of the committed sea level rise that occurred during the 22nd century, with additional increases of 10 and 18 cm from thermal expansion for the two models for the stabilized B1 experiment, and 14 and 21 cm for A1B as compared to year 2200 values. Sea level rise would continue for at least two more centuries beyond 2300, even with these stabilized concentrations of GHGs (*2*).

The meridional overturning maximum in the North Atlantic, indicative of the thermohaline circulation in the ocean, is stronger in the preindustrial simulation in the PCM (32.1 sverdrups) compared to the CCSM3 (21.9 sverdrups), with the latter closer to observed estimates that range from 13 to 20 sverdrups (*25*–*27*). The mean strength of the meridional overturning and its changes are an indication of ocean ventilation, and they contribute to ocean heat uptake and consequent time scales of temperature response in the climate system (*12*, *24*, *28*).

The model with the higher sensitivity (CCSM3) has the greater temperature and sea level rise response at the year 2100 for the B1, A1B, and A2 scenarios (Fig. 1, B and C) and also the larger decrease in meridional overturning in the North Atlantic (–4.0, –5.3, and –6.2 sverdrups or –18, –24, and –28%, respectively) as compared to the model that is less sensitive (PCM), with the lower forced response for B1, A1B, and A2 with decreases of meridional overturning in the Atlantic that are about a factor of 2 less (–1.0, –3.5, and –4.5 sverdrups, or –3, –11, and –14%, respectively). This is consistent with the idea that a larger percentage decrease in meridional overturning would be associated with greater ocean heat uptake and greater surface temperature warming (*12*, *24*).

The warming commitment for 20th-century forcing held fixed at year 2000 values is larger in the CCSM3 than in the PCM (0.6° versus 0.4°C). This is also consistent with the recovery of the meridional overturning in the 21st century after concentrations are stabilized in the PCM (net recovery of +0.2 sverdrups) compared to the CCSM3 (meridional overturning continues to weaken by –0.3 sverdrups before a modest recovery).

Therefore, the PCM, with less climate sensitivity and lower TCR but with greater mean meridional overturning in the Atlantic, has less reduction of North Atlantic meridional overturning and less forced response. The meridional overturning recovers more quickly in the PCM, contributing to even less warming commitment after concentrations are stabilized at year 2000 values. On the other hand, the CCSM3, with higher sensitivity and weaker mean meridional overturning, has a larger reduction of meridional overturning due to global warming (and particularly a larger percent decrease of meridional overturning) than the PCM and contributes to more warming commitment for GHG concentrations stabilized at year 2000 values.

The processes that contribute to these different warming commitments involve small radiative flux imbalances at the surface (on the order of several tenths of a watt per square meter) after atmospheric GHG concentrations are stabilized. This small net heat flux into the ocean is transferred to the deeper layers through mixing, convection, and ventilation processes such as the meridional overturning circulation that connects the Northern and Southern Hemisphere high-latitude deep

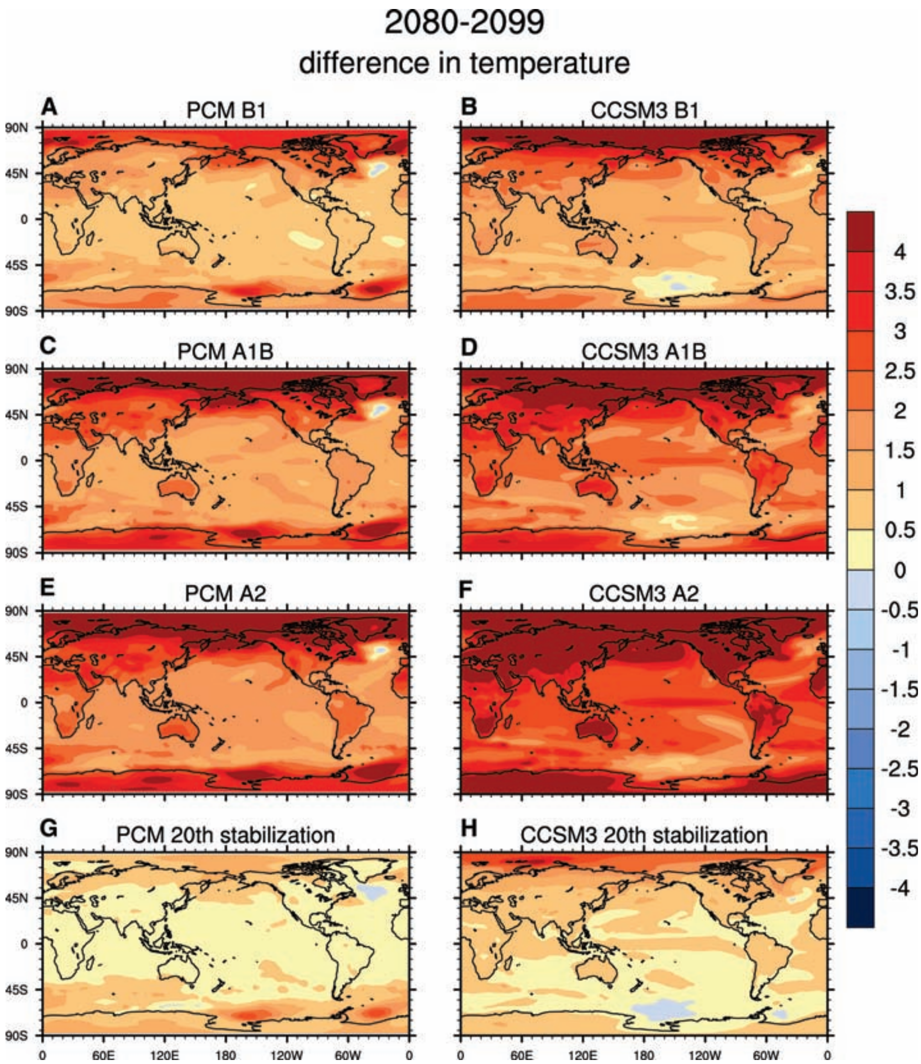

Fig. 2. Surface temperature change for the end of the 21st century (ensemble average for years 2080–2099) minus a reference period at the end of the 20th century (ensemble average for years 1980–1999) from 20th-century simulations with natural and anthropogenic forcings. (**A**) The PCM for the B1 scenario. (**B**) The CCSM3 for the B1 scenario. (**C**) The PCM for the A1B scenario. (**D**) The CCSM3 for the A1B scenario. (**E**) The PCM for the A2 scenario. (**F**) The CCSM3 for the A2 scenario. (**G** and **H**) Temperature commitment for GHG concentrations stabilized at year 2000 values; ensemble average for years 2080–2099 minus a reference period ensemble average for years 1980–1999 from 20th-century simulations. More than 95% of the values in each panel are significant at the 10% level from a Student's *t* test, and a similar proportion exceed 1 SD of the intraensemble standard deviations.

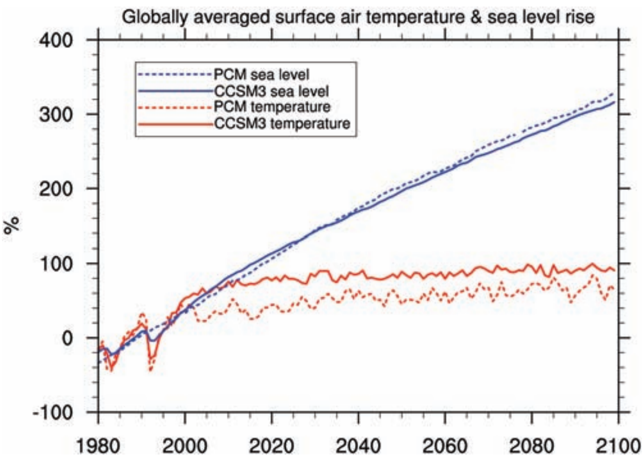

Fig. 3. Ensemble mean percent increase of globally averaged surface air temperature and sea level rise from the two models computed relative to values for the base period 1980–1999 for the experiment in which GHG concentrations and all other atmospheric constituents were stabilized at the end of the 20th century.

ocean circulations (*29*). Thus, in addition to changes in the meridional overturning circulation, the strength of the mean circulation also plays a role (*12*, *24*, *28*). The temperature difference between the upper and lower branches of the Atlantic meridional overturning circulation is smaller in the PCM than in the CCSM3 because of the stronger rate of mean meridional overturning in the PCM that induces a greater heat exchange or ventilation between the upper and deeper ocean. In the PCM, recovery of the meridional overturning is more rapid in the 21st century, thus producing even greater mixing and less warming commitment, whereas the CCSM3 recovers more slowly, with greater warming commitment by the year 2200 and on to 2300.

Geographic patterns of warming (Fig. 2) show more warming at high northern latitudes and over land, generally larger-amplitude warming in the CCSM3 as compared to the PCM, and geographic temperature increases roughly proportional to the amplitude of the globally averaged temperature increases in the different scenarios (Fig. 1B). Slowdowns in meridional overturning in the respective models (which are greater percentage-wise in the CCSM3 than the PCM) are not characterized by less warming over northern Europe in either model. The warming produced by increases in GHGs overwhelms any tendency toward decreased high-latitude warming from less northward heat transport by the weakened meridional overturning circulation in the Atlantic. There is more regional detail in the higher-resolution CCSM3 as compared to the PCM, with an El Niño–like response (*30*) in the equatorial Pacific (greater warming in the equatorial central and eastern Pacific than in the western Pacific) in the CCSM3 as compared to the PCM. This is related to cloud feedbacks in the CCSM3 involving the improved prognostic cloud liquid water scheme, as compared to the diagnostic cloud liquid water formulation in the PCM (*31*).

The warming commitment from the 20th-century stabilization experiments (Fig. 2, bottom) shows the same type of pattern in the forced experiments, with greater warming over high latitudes and land areas. For regions such as much of North America, even after stabilizing GHG concentrations, we are already committed to more than an additional half a degree of warming in the two models. The pattern of the 20th-century stabilization experiments is similar to those produced in the 21st-century stabilization experiments with A1B and B1 (not shown).

Though temperature increase shows signs of leveling off 100 years after stabilization, sea level continues to rise unabated with proportionately much greater increases compared to temperature, with these committed increases over the 21st century more than a factor of 3 greater, percentage-wise, for sea level rise (*32*) than for temperature change (Fig. 3). Thus, even if we could stabilize concentrations of GHGs, we are already committed to significant warming and sea level rise no matter what scenario we follow. These results confirm and quantify earlier studies with simple and global models in that the sea level rise commitment is considerably more than the temperature change commitment.

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