Temperature increase of 21st century mitigation scenarios

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Estimates of 21st Century global-mean surface temperature increase have generally been based on scenarios that do not include climate policies. Newly developed multigas mitigation scenarios, based on a wide range of modeling approaches and socioeconomic assumptions, now allow the assessment of possible impacts of climate policies on projected warming ranges. This article assesses the atmospheric CO_2 concentrations, radiative forcing, and temperature increase for these new scenarios using two reduced-complexity climate models. These scenarios result in temperature increase of 0.5–4.4°C over 1990 levels or 0.3–3.4°C less than the no-policy cases. The range results from differences in the assumed stringency of climate policy and uncertainty in our understanding of the climate system. Notably, an average minimum warming of $\approx$1.4°C (with a full range of 0.5–2.8°C) remains for even the most stringent stabilization scenarios analyzed here. This value is substantially above previously estimated committed warming based on climate system inertia alone. The results show that, although ambitious mitigation efforts can significantly reduce global warming, adaptation measures will be needed in addition to mitigation to reduce the impact of the residual warming.

climate | climate policy | stabilization | integrated assessment | scenario

A key indicator for climate change is the expected global-mean surface temperature increase. Future global temperature changes will be determined primarily by future emissions of greenhouse gases, ozone, and aerosol precursors and the response of the Earth system to those emissions. Any calculation of the potential range of future climate change requires consideration of both a plausible range of emissions scenarios and uncertainties in Earth system response, preferably by using results from multiple scenarios and models. The present analysis aims to map out the potential benefits of climate mitigation actions in terms of how much temperature increase can be avoided as a function of abatement effort. By including scenarios that are among the most stringent in the current literature, the analysis also provides quantitative insight into how much warming is likely to remain as a result of inertia within the energy system as well as the climate system. Such information is of critical importance in the climate policies that are currently being formulated.

The Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) (1) recently projected that by 2100, global mean surface temperature would increase by 1.1–6.4°C over the 1990 level using the range of illustrative baseline (nonmitigation) emissions scenarios from six energy-economic modeling teams that had been developed in the IPCC Special Report on Emissions scenarios (SRES) (2) (the low end of the range results from the so-called B1 scenario; the upper range from the A1FI scenario). This uncertainty range originates both from the range in emissions scenarios and from the limited understanding of the climate system. Earlier, broadly consistent results for the same scenarios were reported in IPCC's Third Assessment Report (TAR) (3) (1.4–5.8°C), in individual model studies (4), in probabilistic approaches (5, 6), and in multimodel intercomparison studies (7, 8). Others obtained similar estimates of baseline temperature ranges with independently developed nonmitigation scenarios (9). The SRES emissions scenarios, however, do not include explicit policies to mitigate greenhouse gas emissions, which would lower the extent of climate change experienced over the 21st Century. Some work (which is also reported in AR4) has been done on the so-called "climate change commitment," i.e., the warming that would occur if concentrations were kept at the year 2000 levels, with an estimated average value of 0.6°C over the course of the 21st Century (10, 11). However, this climate change commitment is only a hypothetical number because inertia in human systems will result in increasing concentrations in the near future, whereas, in the more distant future, both emissions and concentrations can fall. Scenarios based on credible and feasible mitigation strategies are arguably more relevant for policy making (12). Although there have been analyses based on multigas emissions pathways (e.g., refs. 13 and 14) and mitigation scenarios (15–21), a comprehensive assessment of climate impacts using a range of multigas mitigation scenarios from different models has not yet been made.

Progress in developing multigas mitigation scenarios now allows a comparison between climate consequences of such mitigation scenarios versus baseline scenarios. This comparison considers the major uncertainties: climate sensitivity, carbon

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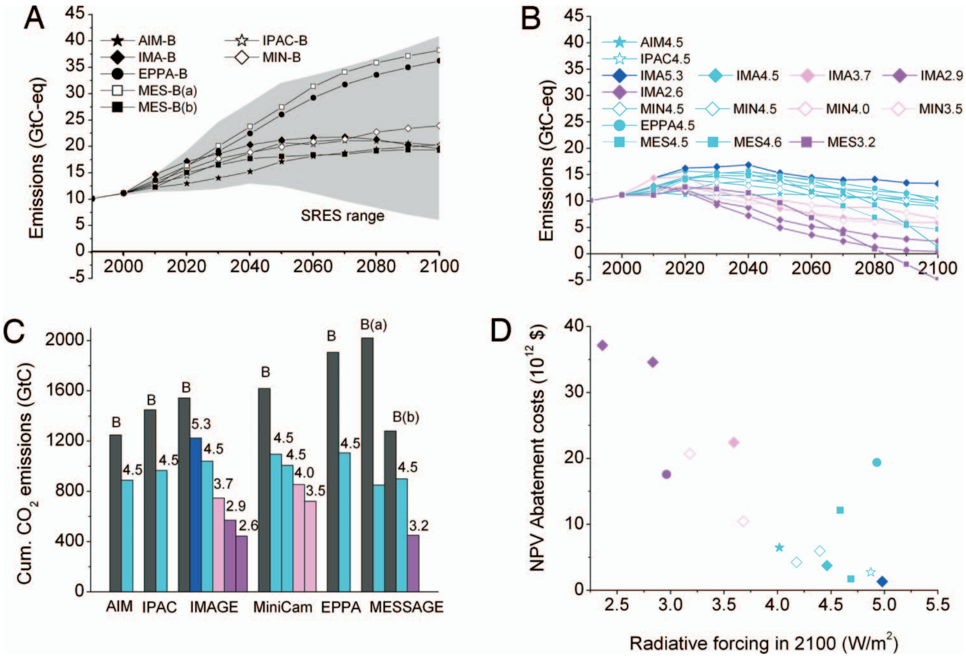

Fig. 1. Emissions of equivalent CO_2 under the baseline scenarios (*A*) and mitigation scenarios (*B*), comparison of cumulative CO_2 emissions (*C*), and the net present value (NPV) of abatement costs (*D*). Emissions in *A* and *B* are expressed in CO_2-equivalent emissions for illustrative purposes. The numbers used to identify the scenarios refer to actual forcing target used within the models. *D* shows the approximate NPV of abatement costs (see *SI Text*) as a function of year-2100 radiative forcing as calculated by MAGICC. The colors indicate the different grouping (black, baseline; light blue, 4.5 W/m^2 stabilization scenarios from EMF-21; dark blue, scenarios with higher stabilization targets than EMF-21; pink, scenarios with targets in between 3.5 and 4 W/m^2; and purple, scenarios with targets <3.5 W/m^2).

cycle processes, socioeconomic modeling approach, climate modeling approach, different baseline assumptions, and climate policy uncertainty (different stabilization levels).

For this article, a set of baseline and associated mitigation scenarios was compiled from a group of Integrated Assessment Models (IAM) with results for the most relevant greenhouse gases and air pollutants (although these model also calculate greenhouse gas concentration and climate change, here, we use only their emission outputs). These models are AIM, EPPA, IMAGE, IPAC, MESSAGE and MiniCAM (22–30). The IAMs include all major greenhouse gases (CO_2, CH_4, N_2O, and halocarbons) and consistent representations of air pollutants, i.e., aerosols (SO_2) and tropospheric ozone precursors (CO, NO_x, VOCs). The mitigation scenarios focus on stabilizing radiative forcing (as a useful integrating metric across agents). Most of the scenarios were developed for the EMF-21 model comparison (31, 32). Together, they represent a wide range of different approaches in modeling the socioeconomic system and capture major uncertainties associated with future emissions.

Here, the radiative forcing and climate implications of the emissions projections were simulated by using two climate models [see supporting information (SI) *Text*]: a relatively simple climate model (MAGICC) (5) and an earth system model of intermediate complexity (Bern2.5CC) (33, 34). Both models simulate atmospheric gas cycles including the effect of air pollutant gases, radiative forcing, and temperature change. In both cases, global emissions were used as model input. MAGICC couples global carbon and gas cycle models with a one-dimensional upwelling diffusion model of ocean heat transport, here tuned to emulate global mean climate responses of 19 coupled atmospheric–ocean models. The Bern2.5CC model combines a zonally averaged dynamic ocean model with models for the atmosphere, thermodynamic sea ice, marine carbon cycle, and dynamic vegetation. Both models have been used extensively in IPCC reports, and the combination is used here to get some representation of model differences as they contribute to uncertainty. For that reason, they are used here in their standard IPCC model setup (see *SI Text*). Results are presented as ranges with climate sensitivity and carbon-cycle parameters varied over plausible ranges. Throughout this article, temperature increase is reported in comparison with 1990 levels, defined as the average over 1980–2000 (see *SI Text* for additional metrics and/or other reference periods sometimes used in the literature).

Emissions Scenarios

In the baseline (no climate policy) scenarios, the range of increase in greenhouse gas emissions by 2100 is from ≈70% to almost 250% compared with 2000 in the absence of climate policy [Fig. 1; emissions are reported in equivalents by using global warming potentials (35) for reporting purposes only]. In all baseline scenarios, emissions growth slows down in the second half of the century because of a combination of stabilizing global population levels and continued technological change. The scenario range used here is reasonably representative of values in the current literature (31) and broadly consistent with the SRES-range. The current set of baseline scenarios lacks cases with substantial declines in emissions over the last part of the 21st Century, which increases the lower end of temperature range for baseline scenarios somewhat compared with AR4, as indicated further below.

The mitigation scenarios necessarily follow a very different pattern, with a peak in global emissions between 2020 and 2040 at a maximum value of 50% above current emissions levels. The mitigation scenarios can be classified into categories according to their radiative forcing target. A large group of the scenarios (8 of 15) aim for stabilization (*ca.* 2150) at 4.5 W/m^2 compared with preindustrial, which was the target of the EMF-21 exercise (hereafter referred to as "4.5 W/m^2" target). Note that the results presented here do not necessarily stabilize at 4.5 W/m^2 when simulated through the climate models used here because

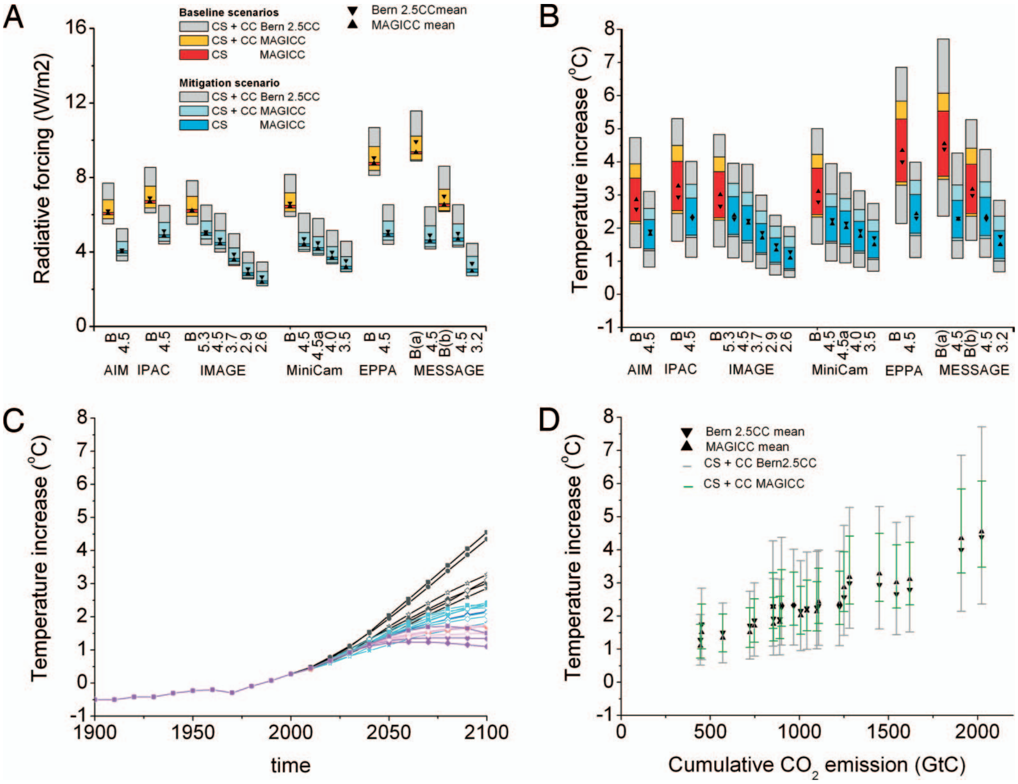

Fig. 2. Radiative forcing and temperature change in year 2100 (*A* and *B*), transient temperature change (*C*) and 2100 temperature increase as a function of cumulative emissions (*D*). Radiative forcing relative to a preindustrial state and temperature change relative to 1980–2000 are given for baseline (red) and mitigation (blue) scenarios (*A* and *B*). Central values are shown as symbols and uncertainty ranges as color bands. Uncertainty ranges in MAGICC originate from the 19 MAGICC runs emulating different AOGCMS (mean ± 1 σ across 19 MAGICC runs) with darker area showing the impact of climate sensitivity only (CS; CS range is 2.0–4.9°C), and the lighter shaded uncertainty ranges show the combined effect of climate sensitivity (CS) plus carbon cycle response (CC) uncertainties (i.e., CS + CC). The full Bern2.5CC model ranges (CS + CC) were obtained by combining different assumptions about the behavior of the CO_2 fertilization effect, the response of heterotrophic respiration to temperature, and the turnover time of the ocean, thus approaching an upper boundary of uncertainties in the carbon cycle (CC), and additionally accounting for the effect of varying climate sensitivity (CS) from 1.5 to 4.5°C. *C* includes the increase of global mean temperature over time for MAGICC (using the same color codes and symbols as Fig. 1). *D* shows the temperature increase (mean and CS + CC range) for both climate models as a function of cumulative CO_2 emissions from 2000 to 2100.

they may represent the carbon cycle and the fate of gases somewhat differently than did the original modeler. This group of scenarios shows cumulative CO_2 emissions of 850-to 1,000 Gigaton Carbon (GtC) (Fig. 1*C*), on average reduced by 40% compared with the baseline. One mitigation scenario has higher (1,100 GtC) and several have considerably lower cumulative emissions (400–850 GtC). The lowest scenarios (IMAGE29, IMAGE26, MESSAGE32—purple in Figs. 1 and 2*C*) have forcing targets <3.5 W/m^2 (hereafter referred to as "lowest scenarios").

The mitigation scenarios are developed in each of the integrated assessment model by selecting a cost-effective set of emission reduction measures. In general, most reductions are obtained by reducing energy-related CO_2 emissions (70–90% of reductions across the scenarios), followed by non-CO_2 gases (15–30%) and CO_2 from land-use (relatively small contribution; both positive and negative as side effects of other reductions measures). Energy-related CO_2 emissions are generally reduced by increases in energy efficiency and application of low/zero carbon energy technologies. In terms of timing, models aim to avoid drastic emission reductions that require (costly) premature reduction of capital; in other words, emission reductions are bounded by the inertia of capital replacement in the energy system. The emission reductions in 2050 vary considerably as a function of the stabilization target. For the 4.5 W/m^2 target, year-2050 emissions are 2–30% lower than the year-2000 emissions, but for the category of lowest scenarios, emissions are 20–60% lower than in year 2000. The category of lowest scenarios tend to push the limits in terms of rate and direction of technological and lifestyle changes. For example, they include the use of bioenergy in combination with carbon-capture and storage, which provides the possibility of net negative emissions from electricity production (36). These scenarios are among the lowest emissions scenarios currently found in the literature (17).

Air pollutant emissions are always lower in the mitigation scenarios than in the baseline scenarios (e.g., 19–88 Teragram Sulphur (Tg S)/yr for the baseline scenarios versus 4–54 Tg S/yr for the mitigation scenarios in 2100). CO_2 emissions reduction and SO_2 emissions reduction are tightly coupled ($r^2 = 0.64$; slope = 1.08); a correlation is also found for NO_x, VOCs and CO (*SI Text*). These correlations result from the changes induced by climate policies in the energy system and are important because these gases also influence radiative forcing via aerosol and ozone formation. In the short term, the coupling between SO_2 and CO_2 emission reduction is crucial because part of the reduced warming resulting from lower CO_2 emissions is offset by additional warming due to reduced SO_2 emissions (37).

The change in abatement cost as a function of the policy target, here represented by radiative forcing in 2100, is shown in Fig. 1*D* (see *SI Text*). As a generic costs measure, the net present value (NPV) of abatement costs is used. The general result is a strong correlation between more ambitious targets and increasing costs. The costs for any particular target varies substantially depending on assumptions for technological options considered, the rate of technological change, substitution between production factors (e.g., capital and energy), recycling of tax revenues, and baseline emissions (38). For the 4.5 W/m^2 target, the net present value of abatement costs from 2000 to 2100 range from 2 to 19 trillion 2000-US$ across the models. The highest cost levels (for the most stringent targets) are equivalent to about 2–3% of NPV of GDP (see also *Discussion and Conclusions*).

Outcomes of the Climate Models

Radiative forcing (Fig. 2*A*) shows the integrated effect of the complete suite of greenhouse gases, aerosols, and precursors and stratospheric and tropospheric ozone. Baseline case forcing in 2100 for central parameters ranges from 6 to 10 W/m^2 compared with preindustrial over the range of emissions scenarios. Forcing in mitigation cases is stabilized or declining by 2100, with values reduced to 2.4–5.1 W/m^2. Both the MAGICC and Bern2.5CC models show similar results for central climate and carbon cycle parameters. The uncertainty ranges, however, are not directly comparable. For Bern2.5CC, the range results from plausible assumptions on upper and lower limits for carbon sequestration by land and ocean (34). For MAGICC, the range is the ±1 standard deviation range across a set of 19 MAGICC runs (see *SI Text*).

The carbon dioxide concentrations for the baseline cases range from 650–950 ppm in 2100 by using central model parameters (for both climate models). Carbon dioxide concentrations in the mitigation scenarios range from 380 to 620 ppm in 2100. The subset of 4.5 W/m^2-target scenarios yields a CO_2 concentration range of 500–590 ppm for central carbon-cycle/climate parameters.

Projected temperature changes by year 2100 (relative to 1990) are 2.6–4.6°C (Fig. 2*B*) for the baseline scenarios and central (best-estimate) model parameters. Uncertainties in the carbon cycle and climate sensitivity more than double the ranges associated with emissions to 2.1–6.1°C in MAGICC and results in an even wider range of possible outcomes in the Bern2.5CC model of 1.4–7.7°C. The range of MAGICC outcomes is on the low end of the range somewhat higher than the numbers reported in TAR and AR4 (1.1°C) as a result of the fact that here no scenarios have been considered that significantly reduce emissions without climate policy (1, 3). Apart from this, the numbers are broadly consistent.

For the mitigation scenarios, the projected temperature changes by 2100 are 1.1–2.4°C by using central model parameters. The mitigation scenarios bring down the overall range of temperature change substantially relative to the baseline range with the largest impact on the high end of the range, which is lowered by >3°C. The greatest difference compared with the baseline is seen during the second part of the century, when the rate of temperature change slows considerably in all mitigation scenarios in contrast to the baseline scenarios. By the end of century, the rate of temperature change under the mitigation scenarios is considerably below the rate of the baseline scenarios (which still show strongly increasing temperature). In fact, under default assumptions in climate parameters in several mitigation scenarios, surface air temperature has more or less stabilized by year 2100. In other words, the policy scenarios have even a greater impact on the additional warming beyond 2100 than the differences reported for that particular year. For the 4.5 W/m^2 target, climate model simulations result in a 2100 temperature increase of 0.8–4.4°C (full Bern2.5CC range).

The temperature increase is 1.1–1.7°C for the central model parameter settings for the lowest emissions scenarios, with a full range of 0.5–2.8°C in the Bern2.5CC model (Fig. 2). Thus, even under these low scenarios, global mean temperature increase could exceed 2°C compared with 1990 depending on climate or carbon-cycle parameters. Assuming that these scenarios represent a lower bound on feasible emissions reductions, these results represent an estimate of the "minimum warming" that considers inertia of both the climate system and socioeconomic systems. The average warming of these scenarios is 1.4°C, of which ≈0.6°C is due to the climate system inertia alone (6). The socioeconomic and technological inertias thus account for ≈0.8°C additional warming by 2100 relative to 1990.

The temperature change in the different scenarios is closely related to the 1990–2100 cumulative carbon emissions (industrial and land-use change), with deviations varying according to other emissions (air pollutants, non-CO_2 greenhouse gases) and emissions pathway. The correlation between cumulative industrial CO_2 emissions and temperature change in 2100 yields a standard deviation of 0.2°C (*SI Text*). Deviations from a perfect correlation are due mainly to the effects of non-CO_2 greenhouse gases.

Discussion and Conclusions

We have examined a large set of projections for 21st Century emissions of a suite of greenhouse and other air pollutant gases. The emissions scenarios provide an indication of the potential effects of mitigation policies. In interpreting these results, however, it should be noted that most of the emissions models used are idealized in many ways. New technologies and policies are assumed to be globally applicable and are often introduced over relatively short periods of time. Especially in the lowest scenarios, it is assumed that some form of global climate policy can be implemented shortly after 2010, as a result of which global emissions can peak *ca.* 2020. On the other hand, some future mitigation options might not have been considered to the full extent. The scenarios here do not generally deal with the question of political feasibility and assume, for example, that mitigation policies are implemented globally and in all sectors of the economy.

Consider first the 4.5 W/m^2 scenarios, which represent a stabilization target of the magnitude often considered by energy-economic analyses. Global emissions in these scenarios begin to diverge from baseline values *ca.* 2020–2030, with emissions dropping to approximately present levels by 2100. Achieving any of these emissions pathways is likely to be challenging compared with past and present mitigation efforts, although views on the magnitude of this challenge differ widely. Temperature starts to diverge from the baseline projections later than emissions. This delay emphasizes the importance of early decisions to meet specific mitigation targets. By the end of the century, the climate consequences of the 4.5 W/m^2 target scenarios result in temperature changes of 0.8–4.4°C relative to 1990 average instead of a warming of 1.4–7.7°C for the baseline projections. Central model parameter settings in 2100 result in ≈2.1°C for the 4.5 W/m^2 target instead of 2.4–4.6°C for the baseline projections. It should be noted that the mitigation scenarios also have a lower warming commitment beyond 2100 than the baseline scenarios.

The lowest scenarios result in a warming of 0.5–2.8°C (average 1.4°C). These scenarios provide a guide to the range of global-mean warming that may occur, assuming ambitious climate policy. The value could be interpreted as a more realistic minimum warming based on technological and economic inertia (although given the nature of uncertainty in emission modeling, the lower bound given here is not a formal one; it simply reflects the assumptions of what is possible based on model assumptions). Its value is substantially above previously estimated committed warming due to climate system inertia only [0.2–1.0°C; (10, 11)]. It should be noted that these scenarios depart from the corresponding no-climate-policy baseline by 2015–2020. Furthermore, they incorporate the widespread development and deployment of existing carbon-neutral technologies in coming decades and, subsequently, of new carbon-neutral technologies. Although the integrated assessment/energy economics model runs indicate that these scenarios may be technically feasible, they clearly require sociopolitical and technical conditions very different from those now existing.

Under the lowest scenarios analyzed here, therefore, meeting a target of 2°C temperature change relative to preindustrial conditions (i.e., 1.5°C relative to 1980–2000) is possible, but is not at all guaranteed. Obviously, the chances of meeting the target decrease substantially for less-stringent stabilization targets. Given the large uncertainty ranges resulting from our limited understanding/knowledge of climate sensitivity and carbon cycle processes, the results reconfirm the need to formulate targets in probabilistic terms (5, 39, 40). Our results show that even the lowest scenarios available in literature, based on optimistic assumptions with respect to international cooperation in climate policy, lead to considerable increases in global mean temperature. These results show that adaptation measures will be needed in addition to mitigation to reduce the impact of the residual warming.

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Supporting Information

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SI Text

Overall Description of Methods. ***Emission scenarios.*** An emission database was compiled from recently published multigas stabilization scenarios. Most of these scenarios have been developed as part of the Stanford University-based Energy Modeling Forum (EMF) (1, 2) (for individual model description see below). Criteria for including scenarios here were coverage of relevant greenhouse gases (GHG) and radiatively important substances as well as publication in peer-reviewed literature. Not all integrated assessment models reported halocarbon in the detail required by the climate models. If that detail was not available, emissions were broken down by using the MiniCam results.

Harmonization. To allow a comparison, the emission scenarios were harmonized to common values for a base year. Emission values were set to the mean value of available emission inventories for the year 2000 by using gas-dependent scaling factors. These scaling factors were assumed to linearly converge to 1 in 2100 (see below).

Cost calculations. For cost calculations, we use a metric that can be computed for all these models, the net present value (NPV) of emission abatement cost; this is a proxy of the economic cost of an abatement policy allowing comparison across very different models. Abatement cost was defined as the abated emissions times the marginal price of carbon-equivalent emission reduction divided by 2.

$$\mathrm{NPV(AC)} = \int_{2010}^{2100} (1/(1+0.05)^{t-2000}*(E_{BL} - E_{Stab})*P_{mar}/2)\,\mathrm{d}t$$

E_{BL} and E_{Stab}(emissions of the stabilization and baseline scenario) and P_{mar} (marginal price) are all calculated by the Integrated Assessment Model and vary over time.

Division by 2 is assumed to represent the fact that most reduction measures are not implemented at the marginal price but at much lower prices. In most cases, the relationship between emission reduction and the marginal price is a concave curve, which implies that a value >2 needs to be used. We have tested the relationship between the NPV calculated by the formula above and the NPV calculated on the basis of the real shape of the cost curve in IMAGE, MiniCam, and MESSAGE and found values ranging from slightly >2 up to 3–4, with higher values found for more stringent reduction targets. The value of 2, used here for simplicity (because the exact value is not known for the other models used here), leads thus to an overestimation of costs.

Climate modeling. The emission data have been used as input for the simple coupled gas-cycle climate model MAGICC and the Bern2.5CC intermediate-complexity climate–carbon cycle model. Extended model descriptions including references are given in *Model Descriptions: Climate and Integrated Assessment Models* below. Both models have been used in the IPCC Fourth Assessment Report (3). The reason to use these two models is to get a representation of the relevant uncertainties. The models are used here in their standard IPCC model setups.

Uncertainty ranges for the two climate models have been generated by considering impacts of climate sensitivity (CS)- and carbon cycle (CC)-related uncertainties individually and in combination (CS + CC). Ranges in MAGICC originate from 19 MAGICC runs emulating different coupled atmosphere/ocean general circulation models (AOGCMs) (mean ± 1 SD across 19 MAGICC runs, emulating different AOGCMS) The Bern2.5CC model ranges were obtained by combining different bounding assumptions regarding the behavior of the CO_2 fertilization effect, the response of heterotrophic respiration to temperature, and the turnover time of the ocean, thus approaching an upper bound of uncertainties in the carbon cycle. The effect of varying climate sensitivity from 1.5°C to 4.5°C has also been taken into account.

Harmonization of Emissions. We harmonize year-2000 emissions of the different scenarios to improve comparability. Various emission inventories of emissions for year 2000 are available, but it should be noted that emission estimates are affected by inevitable degrees of uncertainty. CO_2 emissions from energy and industrial sources are relatively well researched compared with other sources, but still, the most commonly used inventories for this source differ by ≈5% (see Table S1).

We used the mean of the available, most relevant inventories for our harmonization (Table S1). The differences among the various inventories for emissions other than CO_2 are typically in the order of 10–15% of emissions. Interestingly, for most sources, the uncertainties in the base year emissions of the models used in this article are similar to the uncertainties in the estimates of the various inventories. In several cases, however, the mean of the inventories is different from the mean of the modeling results (CO_2, NO_x, CO).

Emissions of Halogenated Gases. The various halogenated gases have very different atmospheric lifetimes and radiative properties. Unfortunately, most models classify these gases using very different systems. For the calculations in the climate models, we used the classification as indicated in Table S1. Therefore, we used a downscaling method to develop this information consisting of the steps below (directly available data were used instead for IMAGE and MiniCam): Emissions were first calculated for the emissions categories for which information was available, by using the normal harmonization procedure (categories of halogenated gases HFC, HFC23, PFC, and SF6).

These categories were then further broken down into the various gases by using the gas fractions in their respective aggregates of the MiniCam scenario.

Model Descriptions: Climate and Integrated Assessment Models. ***Climate models.*** *MAGICC.*

MAGICC is a simple coupled gas-cycle/climate model (4). MAGICC has been calibrated against a range of coupled atmosphere/ocean general circulation models (AOGCMs) 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. In this study, MAGICC was run with calibration parameter sets to emulate output from 19 AOGCMs provided in the Program for Climate Model Diagnosis and Intercomparison (PCMDI) database (www-pcmdi.llnl.gov/) in preparation for the fourth IPCC Assessment report. The global carbon cycle response was adjusted to approximately emulate the lower-, medium-, and high-range CO_2 concentrations under the SRES A2 scenario [IPCC's Special Report on Emission Scenarios (5)] as provided by the World Climate Research Programme (WCRP) CMIP3 multimodel dataset of various carbon cycle models (6). Thus, for each emission scenario, 57 (equal to 19 × 3) runs were integrated with MAGICC. The means represent the averages across 19 AOGCM emulations with medium carbon cycle settings. The ranges provided in the main text over climate and carbon cycle uncertainty are the means ± 1 standard deviation (SD) for the subset of runs that assume high and low carbon cycle feedbacks.

Bern2.5CC. The Bern2.5CC reduced complexity climate model (7) includes components describing (*i*) the physical climate system, (*ii*) the cycling of carbon and related elements, and (*iii*), a module to calculate concentrations of non-CO_2 GHGs and radiative forcing by atmospheric CO_2, non-CO_2 GHGs, and aerosols (8, 9). The Bern2.5CC model is the latest of the Bern models used in all four IPCC Assessment Reports and in various IPCC technical papers and special reports.

The ocean physical component is the zonally averaged, three-basin circulation model of Stocker *et al.* (10), coupled to a zonally and vertically averaged atmospheric energy balance model (EBM), including an active hydrological cycle (11). The physical model setup and parameters are described in ref. 8. The ocean biogeochemical component is a simple description of the cycles of carbon, carbon isotopes, oxygen, and carbon-related tracers (12). Phosphate is taken as the biolimiting nutrient, and temporally and spatially constant stoichiometric ratios between biogenic fluxes were assumed. A prognostic description of export production was applied to account for changes in the ocean carbon cycle and atmospheric CO_2 driven by changes in ocean circulation (8).

The terrestrial biosphere component is the Lund–Pottsdam–Jena dynamic global vegetation model (LPJ-DGVM) at a 3.75 × 2.5° resolution as used by Joos *et al.* (9) and described in detail in refs. 13–15. The LPJ-DGVM is forced by Cramer/Leemans annual mean climatology plus interannual climate variability from the Hadley simulation (30-year recycled climate) plus changes in the fields of surface temperature, precipitation, and cloud cover. The cloud cover is calculated by means of scaling spatial patterns (9) with the global-mean surface temperature simulated by the EBM in response to projected radiative forcing. Land-use changes are not explicitly considered in the present simulations. Instead, carbon fluxes from land-use changes are prescribed externally in emission scenarios. The impact of climate change on terrestrial C-storage is included.

Finally, the module designed to calculate radiative forcing by atmospheric CO_2, non-CO_2 GHGs, and aerosols is based on work summarized in Fuglestvedt and Berntsen (16) and Joos *et al.* (9).

The different components of the Bern2.5CC climate-carbon cycle model have been tested and applied in a range of studies investigating past, present, and future carbon cycle behavior and its impact on climate (e.g., refs. 8, 9, 12, and 17–25). Results are broadly consistent with those from more comprehensive AOGCMs, coupled climate models, and observations.

The Bern2.5CC model ranges are based on the approach used in IPCC Third Assessment Report (9, 26): the low-CO_2 case was obtained by applying a fast mixing ocean and assuming heterotrophic respiration to be independent of global warming; the high-CO_2 case was obtained by applying a slow mixing ocean and capping CO_2 fertilization after the year 2000. Calculated anthropogenic emissions in the year 2000 for lower and upper bounds are 7.4 and 9.4 GtC/yr respectively, in accordance with the range of data-based estimates (27). Average ocean carbon uptake over the 1980–2000 period ranges between 1.91 and 2.53 GtC/yr, uptake from 1800 to 1995 is between 116.1 and 159.8 GtC and, thus, at the upper end of the current range of observational estimates (27). The effect of varying climate sensitivity from 1.5 to 4.5°C has been also taken into account. The model reference case is obtained with midrange behavior of the carbon cycle and a climate sensitivity of 3.2°C.

Integrated assesment models. *IMAGE.* IMAGE is an integrated assessment model for global change (28, 29). The main objectives of IMAGE are to contribute to scientific understanding and support decision-making by quantifying the relative importance of major processes and interactions in the society–biosphere–climate system. Two main components of the model are the description of the energy system and related emissions (the TIMER energy model) and land use and land cover and related emissions. The model versions used for this article (2.2 and 2.3) distinguish 17 world regions for socioeconomic modeling, whereas a 0.5 × 0.5 grid is used for many environmental parameters (30, 31). For climate change, the IMAGE model uses an adapted version of the MAGICC model in combination with methods for pattern scaling. In the context of climate-change policy scenarios, the IMAGE model is run in conjunction with the FAIR climate policy-analysis model (32). In this setup, IMAGE provides information on baseline emissions and mitigation options, whereas FAIR chooses the set of options that lead to lowest costs given a certain climate target and derived emission profile. The scenarios discussed in this article form a part of the studies published for looking into integrated reduction strategies (30, 31).

AIM. AIM is a generic name of the simulation models developed by the Asian Pacific Integrated Model team. The multiregion/multisector/multigas model AIM/CGE (Asia) was developed to analyze long-term stabilization scenarios. This model is a recursive dynamic computable general equilibrium (CGE) model based on a Global Trade Analysis Project energy–economy dataset (GTAP-EG) structure and programmed with GAMS/MPSGE. GTAP ver.5 database (base year = 1997) is used for the economic database and IEA energy statistics for the energy database. This is a long-term model with a time horizon from 1997 to 2100; it includes 18 world regions and 13 economic sectors (33). The AIM/CGE (Asia) is an update of the AIM/CGE (Energy) model (34) and includes a framework for both CO_2 and non-CO_2 gases. The model serves three sectors—production, household, and government—in each region. CO_2 and non-CO_2 gases are emitted by activities in each of these sectors.

IPAC. Integrated Policy Assessment model for China (IPAC) is a model framework developed by China's Energy Research Institute to analyze energy and emission-mitigation policies with focus on China (35). The IPAC framework is composed of several models including both bottom-up and top-down models, and model development has benefited from collaboration with other institutes. The IPAC-emission model, one of the main models in IPAC, is a revised version of the AIM/emission model developed by the National Institute for Environment Studies (NIES) (33). IPAC's energy sector's top-down module is based on the Edmonds–Reilly–Barns (ERB) model; it includes a partial equilibrium model focusing on the energy market but also an end-use module taken from the IPAC-AIM/technology model. This model provides a detailed energy demand analysis for China before 2030. For other regions, data are mostly used from the AIM, although other information has been added (National Communications, IEA, EIA, etc.). The land-use module was developed from the agriculture and land use (AgLU) model (36). The IPAC model works with nine regions: USA, Western Europe and Canada, Pacific Organisation for Economic Cooperation and Development (OECD), Eastern Europe and Former Soviet Union, China, South and East Asia, Middle East, Africa, and Central and South America. The model runs from 1990 to 2100. The time steps are in units of 5 years up to 2030, followed by time steps for 2050, 2075, and 2100.

EPPA. The Massachusetts Institute of Technology (MIT) Emissions Prediction and Policy Analysis (EPPA) model is a computable general equilibrium (CGE) model. Advantages of CGE models for analysis of environmental policy are their ability to capture the influence of a sector-specific (e.g., energy, fiscal, or agricultural) policy on other industry sectors, consumption, and international trade, and impacts on capital accumulation and growth. The MIT EPPA model is a recursive-dynamic, 17-region CGE model of the world economy (37, 38), with considerable sectoral and energy technology detail, built on the economic and energy data from the GTAP dataset (39, 40) and additional data for the GHG (CO_2, CH4, N_2O, HFCs, PFCs and SF_6) and urban gas emissions (CO, VOC, NOX, SO_2, BC, OC, NH_4) recently updated to include the US EPA inventory data (41), and including endogenous costing of the abatement of non-CO_2 GHGs (42). It has been used extensively for the study of climate policy, climate interactions, and impacts and to study uncertainty in emissions and climate projections for climate models as discussed in greater detail in Paltsev *et al.* (38).

MiniCAM. The calculations presented here were conducted with the MiniCAM 2001 integrated assessment model (see refs. 43 and 44) for the equation structure). Its energy-economy roots can be traced back to Edmonds and Reilly (45). MiniCAM is a partial equilibrium energy–economic–agricultural model that also incorporates the set of climate and atmospheric models known as MAGICC (46, 47). The energy component of the MiniCAM solves world and regional energy supply and demand in 14 world regions from 1990 to 2095 using a 15-year time step. The MiniCAM begins with a representation of demographic and economic developments in each region and combines these with assumptions about technology development to describe an internally consistent representation of energy, agriculture, land-use, and economic developments that in turn shape global emissions and concentrations of GHGs. GHG concentrations in turn determine radiative forcing and climate change. The MiniCAM model focuses strongly on energy production, transformation, and use. The model tracks the production of fossil fuels, namely oil, natural gas, and coal as well as nonfossil primary energy forms including nuclear, wind, solar, and hydro. The model transforms primary energy forms to those that are consumed in final use. Transformation processes include refining, power generation, and hydrogen production. A variety of technology options are available to produce all of the end-use energy forms: liquids, gases, solids, electricity, and hydrogen. Electric generation technologies include fossil fuels (with or without geologic sequestration), biomass, and a number of non-carbon-emitting technologies (wind, solar PV, fusion, nuclear, hydroelectric, etc.). Energy is consumed in three final-use sectors: buildings, industry, and transportation. Emissions of a suite of aerosols and non-CO_2 GHGs are included, based on parameterization of emissions controls on local air pollutants (48–50). The version of the model used to produce the results in this work has now been replaced by an implementation using an object-oriented design paradigm (51).

MESSAGE. MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact) is a systems-engineering optimization model used for medium- to long-term energy system planning, energy policy analysis, and scenario development (52). The model provides a framework for representing an energy system with all its interdependencies from resource extraction, imports and exports, conversion, transport, and distribution to the provision of energy end-use services such as light, space conditioning, industrial production processes, and transportation. The model's current version, MESSAGE IV, provides information on the utilization of domestic resources, energy imports and exports, and trade-related monetary flows, investment requirements, the types of production or conversion technologies selected (technology substitution), pollutant emissions, interfuel substitution processes, and temporal trajectories for primary, secondary, final, and useful energy. MESSAGE is linked to the MACRO economic modeling framework (53, 54) which permits the estimation of internally consistent scenarios of energy prices and energy systems costs—derived from a detailed systems-engineering model (MESSAGE)—with economic-growth and energy-demand projections obtained from a macroeconomic model (MACRO). The framework operates at the level of 11 world regions. Integration of agriculture and forestry sectors in the MESSAGE–MACRO framework has been achieved through linkages to the land-use/climate policy dynamic integrated model of forestry and alternative land use (DIMA) model and the agriculture land use Agricultural Zones Model–Basic Linked System (AEZ–BLS) model. Although potentials for bioenergy supply and CO_2 mitigation via forest-sink enhancement are based on sensitivity analysis of the DIMA model, the AEZ–BLS framework provides important inputs with respect to agricultural drivers of GHG emissions, such as changes in rice cultivation, animal stock, and fertilizer use. In that sense, the MESSAGE–MACRO stands at the heart of the fully integrated IIASA assessment framework (55). Its principal results comprise the estimation of technologically specific multisector response strategies for alternative climate stabilization targets.

Correlation of Air Pollutants and Climate Policy. Fig. S1 shows the data of the various models for (*i*) emission reduction of fossil fuel CO_2 emissions in the mitigation scenarios compared with baseline emissions against (*ii*) the emissions reductions of air pollutants (SO_2, NO_x, VOC, and CO).

For all air pollutants, emission reduction in mitigation scenarios were found to be correlated with CO_2 emission reductions as a result of climate policy-induced systemic changes in the energy system. For SO_2, this relationship even indicates that, on average, emission are reduced on par with CO_2. For the other three gases, emission reductions are smaller than those for CO_2, varying from ≈50% for NO_x to ≈30% for CO.

Key Model Outcomes Using Different Metrics. As indicated in the main text, different metrics are commonly used to describe outcomes of stabilization scenarios in the literature. Tables S2 and S3 summarize some key model outcomes of the MAGICC and Bern2.5CC models by using different common metrics.

Comparison of MAGICC and Bern2.5CC Projections. The graphs in Figs. S2 and S3 compare the Bern2.5CC outcomes for projected CO_2 concentrations and temperature increase for each scenario in 2100 with those for the MAGICC model. The comparison leads to the following conclusions: Under default assumptions for the carbon cycle, the CO_2 concentrations found in MAGICC and Bern2.5CC are very similar.

The variation in results for different carbon cycle assumptions is much larger in Bern2.5CC than in MAGICC, in particular on the high-concentration side.

In general, results show convergence between the two models on the low end of the concentration range.

Conclusions for projected radiative forcing from the two models (data not shown) are very similar to those for projected atmospheric CO_2 based on Fig. S2. This is not unexpected, because CO_2 dominates total anthropogenic radiative forcing. At the same time, however, radiative forcing is also impacted by gases other than CO_2.

The comparison of projected temperature increase also lead to similar conclusions as those indicated for atmospheric CO_2 concentrations.

Comparison of Non-CO_2 Assumptions in the Two Climate Models. Fig. S4 shows model results for the projected temperature change in 2100 as compared with cumulative fossil and land use-related CO_2 emissions from 2000 to 2100. Best-fit lines for the BERN2.5CC and MAGICC models are shown. The results indicate that the 2100 temperature change does strongly depend on the 2000–2100 cumulative emissions (a linear fit results in high regression coefficients). The fit found for the Bern2.5CC model is slightly steeper than the one for MAGICC, The standard deviation of the residuals are 0.26°C and 0.29°C, respectively.

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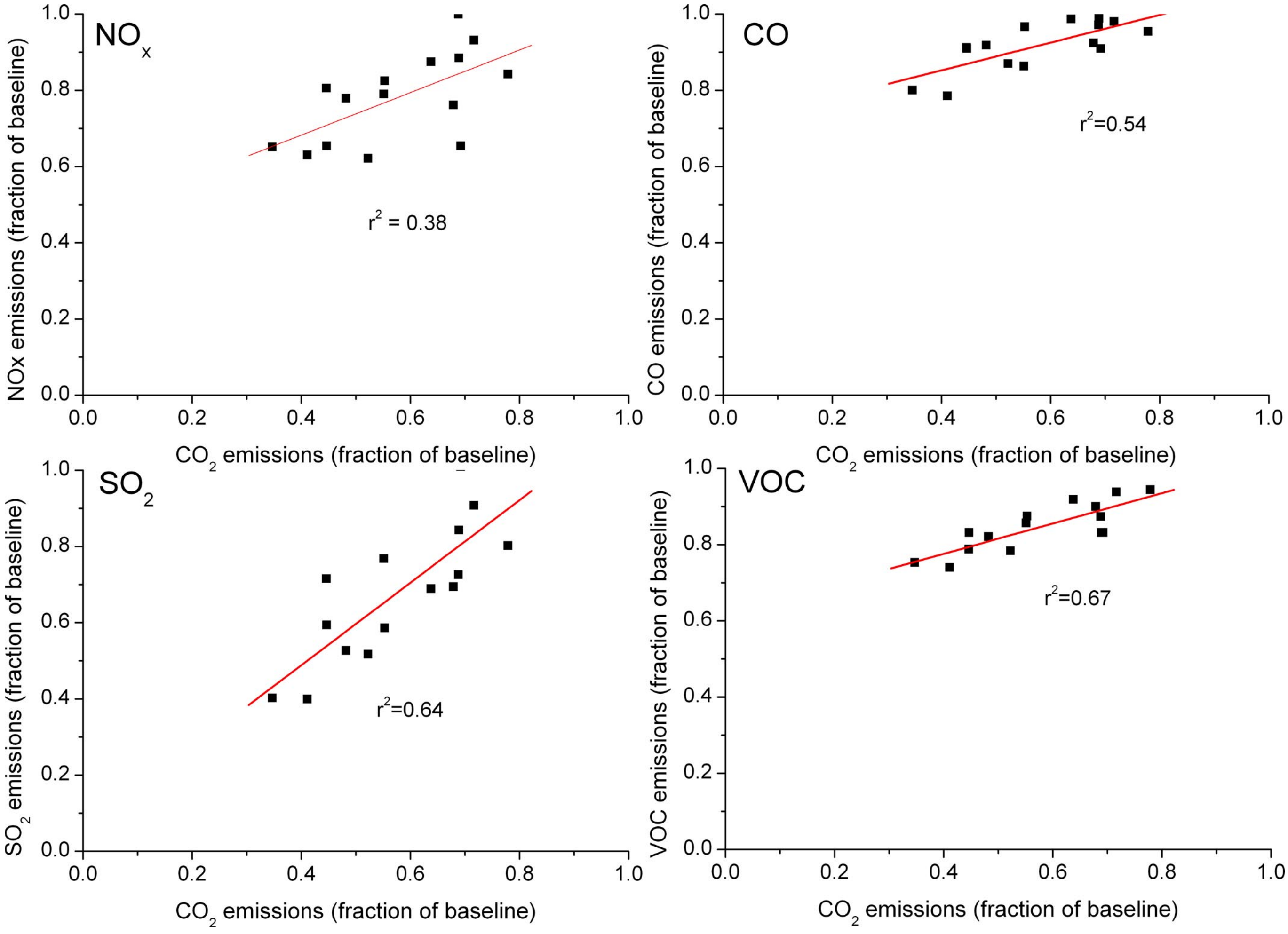

Fig. S1. Emission reductions for fossil fuel CO_2 emission versus emission reductions of air pollutants (NO_x, CO, SO_2 and VOC).

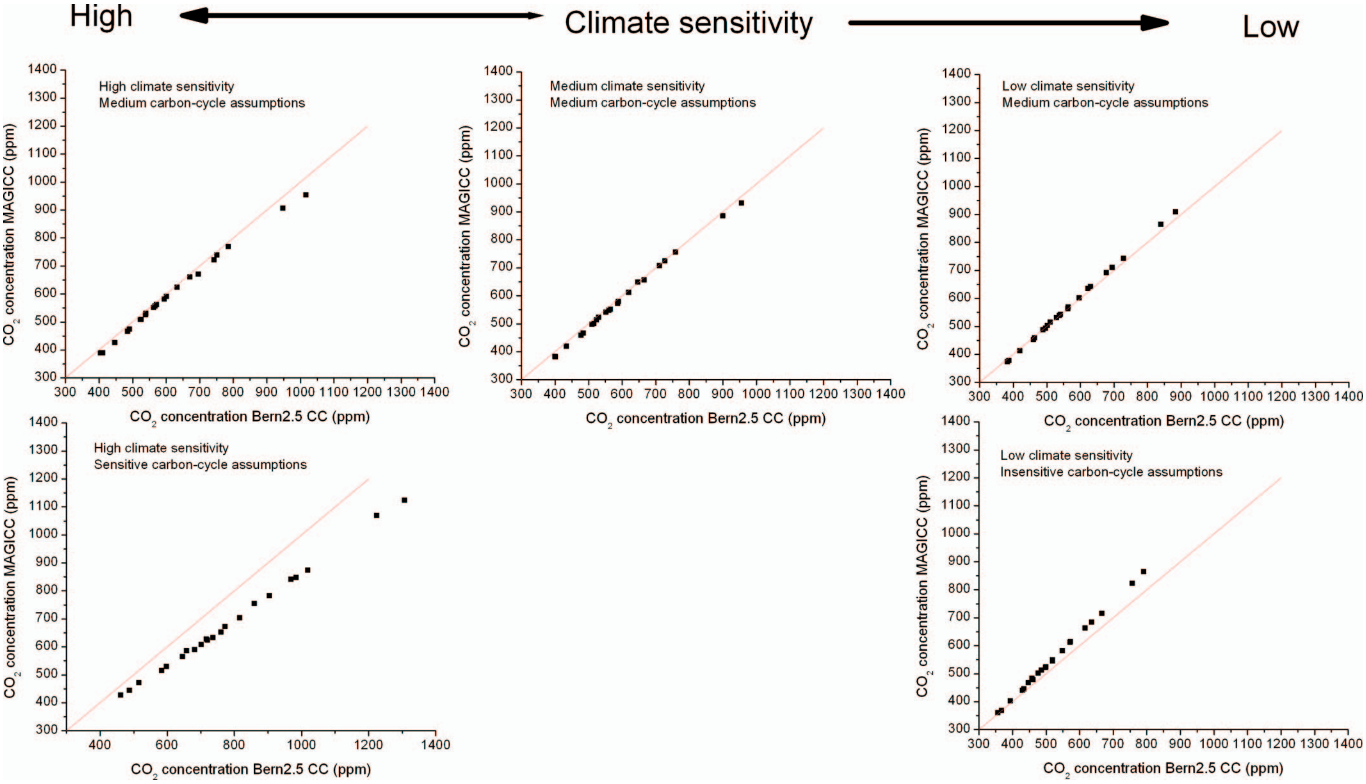

Fig. S2. Results for projected CO_2 concentrations from the Bern2.5CC model versus the MAGICC model. The graphs compare results under different combinations with respect to the climate sensitivity and carbon cycle assumptions. The low and high values for climate sensitivity and carbon cycle assumptions are defined per model as indicated in the model descriptions (see *Model Descriptions: Climate and Integrated Assessment Models* in *SI Text*).

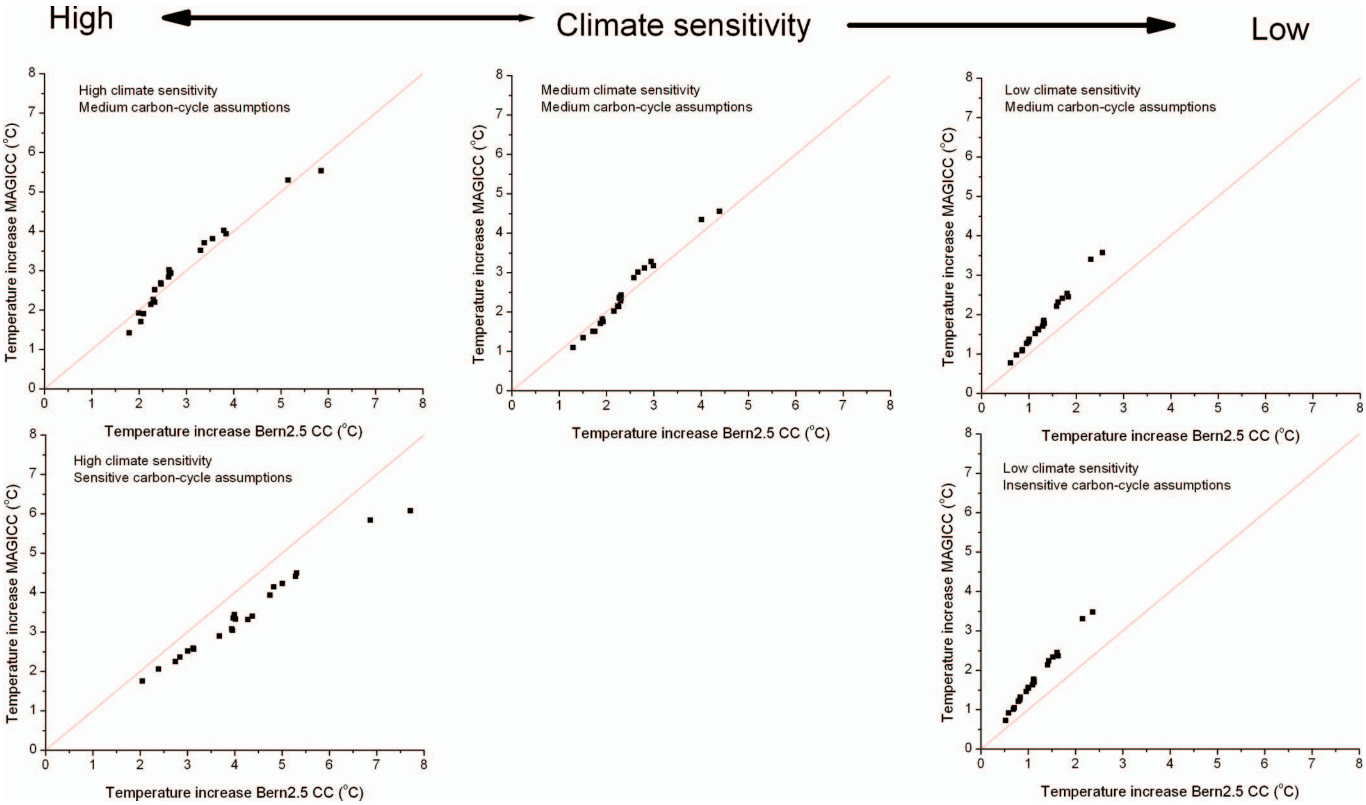

Fig. S3. Results for projected temperature increase for the Bern2.5CC model versus the MAGICC model. The graphs compare results under different combinations with respect to the climate sensitivity and carbon cycle assumptions. The low and high values for climate sensitivity and carbon cycle assumptions are defined per model as indicated in the model descriptions (see *Model Descriptions: Climate and Integrated Assessment Models* in *SI Text*).

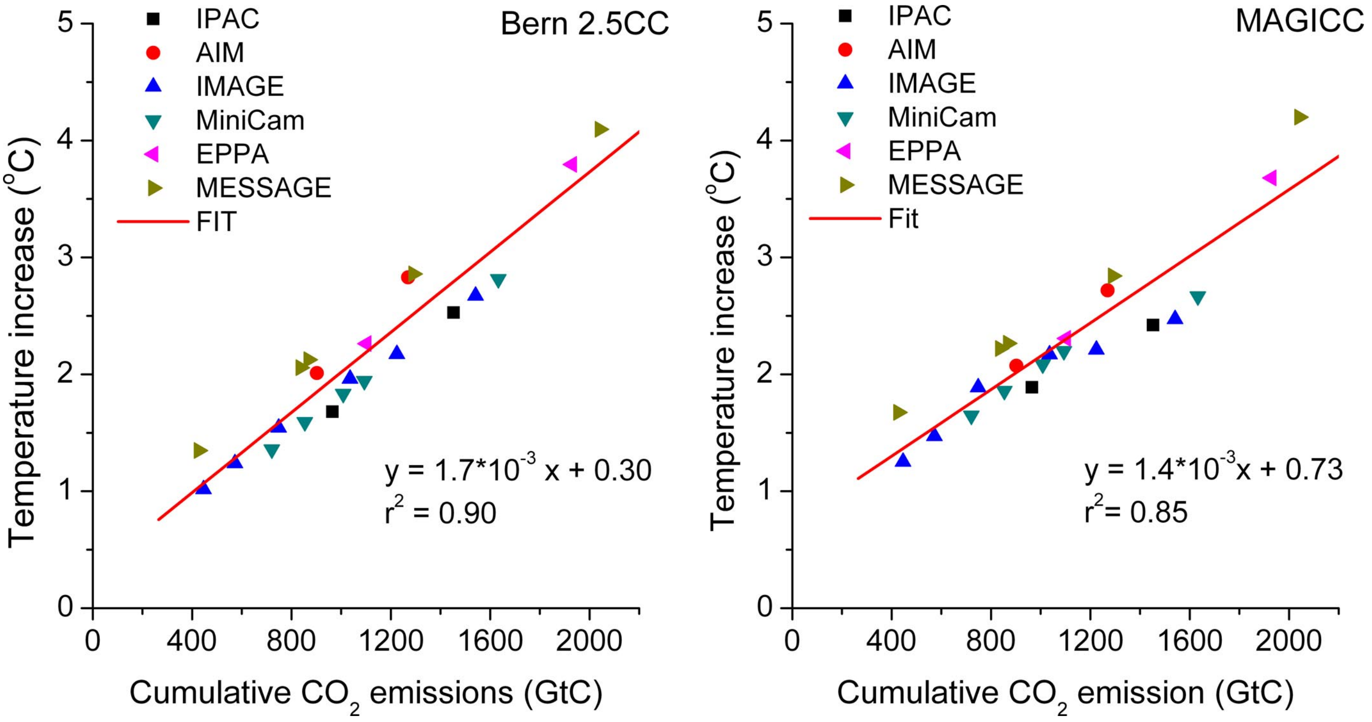

Fig. S4. Projected temperature increase vis-à-vis cumulative CO_2 emissions for the Bern2.5CC model (*Left*) and the MAGICC model (*Right*). The lines indicate the linear regression line for each set of results.

Table S1. Historic emissions according to various emission inventories and emission values used for harmonization in this article

		EDGAR		EPA		Other		Values used for harmonization		Mean models	SRES	
Component	Unit	1990	2000	1990	2000	1990	2000	1990	2000	2000	1990	2000
Foss CO2	GtC	6.5	7.4			6.3 (1), 6.2 (2)	7.2 (1), 6.9 (2)	6.4	7.2	6.8	6.0	6.9
Defo CO2	GtC	0.5	0.7			2.2 (3)	2.1 (3)	1.1	1.1	1.1	1.1	1.1
Total CO2	GtC	7.0	8.2					7.5	8.3	7.9	7.1	8.0
CH4	MtCH4	302.0	321.0	275.7	278.8	366 (4)	326 (4)	288.8	299.9	297.8	309.7	322.9
N2O	Mt N2O-N	7.2	7.8	6.3	6.9			6.7	7.3	6.7	6.7	7.0
NOx	MtN	33.4	38.5			36.1 (4)	36/7 (4)	34.8	37.6	32.6	30.9	32.0
VOCs	Mt	153.2	186.3				250 (5)	153.2	186.3	174.8	139.1	141.4
CO	MtCO	846.0	1076.8			1098 (4)	1046 (4)	972.0	1061.4	898.4	879.0	877.1
SO2	MtS	74.6	79.1			65.7 (6), 70 (7)	54.1 (6) , 62 (7)	70.1	65.1	65.2	70.9	69.0
CF4		0.0105	0.0112	0.0138	0.0096	0.019 (8)	0.017 (8)	0.015	0.013		0.018	0.016
C2F6		0.0019	0.0026	0.0019	0.0027	0.001 (8)	0.001 (8)	0.002	0.002		0.001	0.002
HFC125		0.0000	0.0087			0.000 (8)	0.034 (8)	0.000	0.021		0.000	0.000
HFC134a		0.0000	0.0602			0.000 (8)	0.089 (8)	0.000	0.077		0.000	0.080
HFC143a		0.0000	0.0035			0.000 (8)	0.015 (8)	0.000	0.009		0.000	0.000
HFC227		0.0000	0.0404			0.000 (8)	0.000 (8)	0.000	0.020		0.000	0.000
HFC245		0.0000	0.0000			0.000 (8)	0.037 (8)	0.000	0.018		0.000	0.000
SF6		0.0047	0.0052			0.006 (8)	0.006 (8)	0.006	0.006		0.006	0.006
HFC23		0.0053	0.0067	0.0067	0.0083			0.006	0.007		0.000	0.000

Sources: EDGAR data was collected from the EDGAR website (www.mnp.nl/edgar). EPA data were collected from EPA (2006) *Global Anthropogenic Non-CO2 Greenhouse Gas Emissions: 1990–2020* (US Environmental Protection Agency, Washington, DC). SRES data were collected from Nakicenovic, *et al*. (2000) *Special Report on Emission Scenarios* (Cambridge Univ Press, Cambridge, UK). The data in the other columns are based on the following sources: (1) IEA (2005*) CO_2 Emissions from OECD and Non-OECD Countries* (Organisation for Economic Co-operation and Development , Paris); (2) CDIAC (2006) http://cdiac.esd.ornl.gov/trends/emis/em_cont.htm/; (3) Houghton RA (2003) Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850–2000. *Tellus B* 55 378–390; (4) Cofala J, Amann M, Mechler R (2005) *Scenarios of World Anthropogenic Emissions of Air Pollutants and Methane up to 2030*, Technical report [International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria], available from: www.iiasa.ac.at/rains/global emiss/global emiss.html/; (5) Dentener F, *et al.* (2005). The impact of air pollutant and methane emission controls on tropospheric ozone and radiative forcing: CTM calculations for the period 1990–2030. *Atmos Chem Phys* 5:1731–1755; (6) Cofala, *et al.* see (4) above, but including EDGAR and Smith *et al*. for emissions not covered by Cofala; (7) Smith SJ, Pitcher H, Wigley TML (2005) Future sulfur dioxide emissions. *Clim Change* 73:267–318; (8) Smith SJ, Wigley TML (2006) Multi-gas forcing stabilization with the MiniCAM. *Energy Journal Special Issue* 3:373–391.

Table S2. Key model outcomes MAGICC

		2100			Equilibrium	2100	
						Temperature, °C	
Model	Scenario	CO_2 concentration, ppm (range)	Radiative forcing, W/m^2 (range)	CO2-eq, ppm	Reported, W/m^2	1980–2000 (range)	Preindustrial
AIM	ref	648 (612–754)	6.1 (5.8–6.8)	872		2.9 (2.1–3.9)	3.4
	emf	523 (501–586)	4.0 (3.8–4.6)	593	4.5	1.8 (1.3–2.6)	2.4
IPAC	ref	707 (663–840)	6.7 (6.4–7.6)	980		3.3 (2.4–4.5)	3.8
	emf	541 (512–627)	4.9 (4.6–5.6)	696	4.5	2.4 (1.7–3.3)	2.9
IMAGE	ref	725 (683–847)	6.2 (5.9–7)	895		3.0 (2.2–4.1)	3.6
	emf	552 (524–633)	4.5 (4.2–5.2)	645	4.5	2.2 (1.6–3.1)	2.7
	53	612 (581–703)	5.0 (4.7–5.7)	710	5.3	2.4 (1.7–3.4)	2.9
	37	467 (445–529)	3.6 (3.4–4.2)	548	3.7	1.7 (1.2–2.5)	2.3
	29	420 (402–471)	2.8 (2.6–3.4)	475	2.6	1.3 (0.9–2.1)	1.9
	26	383 (368–427)	2.4 (2.2–2.9)	435	2	1.1 (0.7–1.8)	1.7
MiniCam	ref	756 (715–874)	6.5 (6.2–7.2)	935		3.1 (2.3–4.2)	3.7
	emf	572 (545–652)	4.4 (4.1–5.1)	636	4.5	2.1 (1.5–3)	2.7
	45	548 (521–623)	4.2 (3.9–4.8)	611	4.5	2.0 (1.5–2.9)	2.6
	40	501 (478–565)	3.7 (3.5–4.3)	557	4	1.8 (1.3–2.6)	2.3
	35	459 (440–515)	3.2 (3–3.8)	507	3.5	1.5 (1.1–2.2)	2.1
EPPA	ref	885 (823–1,068)	8.8 (8.4–9.7)	1438		4.3 (3.3–5.8)	4.9
	emf	580 (548–672)	4.9 (4.7–5.7)	703	4.5	2.4 (1.8–3.4)	3.0
MESSAGE	refa	931 (864–1,124)	9.3 (9–10.2)	1606		4.6 (3.5–6.1)	5.1
	emf	498 (468–589)	4.6 (4.3–5.4)	659	4.5	2.3 (1.6–3.3)	2.8
	refb	657 (614–781)	6.5 (6.2–7.4)	949		3.2 (2.4–4.4)	3.7
	46	514 (483–608)	4.7 (4.4–5.5)	672	4.5	2.4 (1.7–3.4)	2.9
	32	382 (361–444)	3.0 (2.7–3.7)	487	3.2	1.5 (1–2.4)	2.1

As reference year for preindustrial temperature, 1860 is used. Warming since preindustrial is approximated by adding 0.6°C to the 1980–2000 values.

Table S3. Key model outcomes Bern2.5CC

		2100			Equilibrium	2100	
						Temperature, °C	
Model	Scenario	CO_2 concentration, ppm (range)	Radiative forcing, W/m^2 (range)	CO2-eq, ppm	Reported, W/m^2	1980–2000 (range)	Preindustrial
AIM	ref	647 (571–860)	6.2 (5.5–7.7)	891		2.6 (1.4–4.7)	3.1
	emf	530 (477–658)	4.1 (3.5–5.3)	603	4.5	1.9 (0.8–3.1)	2.5
IPAC	ref	711 (616–968)	6.9 (6.1–8.6)	1016		2.9 (1.6–5.3)	3.5
	emf	552 (487–717)	5.1 (4.5–6.5)	731	4.5	2.3 (1.1–4.0)	2.9
IMAGE	ref	727 (636–984)	6.2 (5.5–7.8)	897		2.7 (1.4–4.8)	3.2
	emf	565 (499–736)	4.7 (4.0–6.1)	670	4.5	2.2 (1.0–3.9)	2.8
	53	620 (548–816)	5.1 (4.4–6.5)	722	5.3	2.3 (1.1–4.0)	2.8
	37	484 (434–597)	3.9 (3.3–5.0)	578	3.7	1.9 (0.8–3.0)	2.5
	29	434 (394–516)	3.1 (2.6–4.0)	499	2.6	1.5 (0.6–2.4)	2.1
	26	400 (368–462)	2.7 (2.2–3.4)	460	2	1.3 (0.5–2.0)	1.8
MiniCam	ref	759 (667–1,018)	6.6 (5.9–8.2)	963		2.8 (1.5–5.0)	3.3
	emf	586 (519–760)	4.7 (4.1–6.1)	675	4.5	2.3 (1.–3.9)	2.8
	45	561 (498–720)	4.5 (3.8–5.8)	647	4.5	2.2 (1.0–3.7)	2.7
	40	516 (461–645)	4.0 (3.4–5.2)	590	4	1.9 (0.8–3.1)	2.5
	35	478 (429–584)	3.5 (3.0–4.6)	542	3.5	1.7 (0.7–2.7)	2.3
EPPA	ref	899 (757–1,224)	9.0 (8.1–10.7)	1518		4.0 (2.1–6.9)	4.6
	emf	589 (519–773)	5.1 (4.4–6.6)	726	4.5	2.3 (1.1–4.0)	2.9
MESSAGE	refa	956 (791–1,307)	9.9 (8.9–11.6)	1785		4.4 (2.4–7.7)	4.9
	emf	510 (447–681)	4.9 (4.2–6.4)	699	4.5	2.3 (1.1–4.3)	2.8
	refb	665 (573–904)	7.0 (6.2–8.6)	1032		3.0 (1.6–5.3)	3.5
	46	524 (458–701)	5.0 (4.3–6.6)	711	4.5	2.3 (1.1–4.4)	2.8
	32	401 (356–488)	3.4 (2.7–4.4)	526	3.2	1.8 (0.7–2.8)	2.3

As reference year for preindustrial temperature, 1860 is used. Warming since preindustrial is approximated by adding 0.6°C to the 1980–2000 values.