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Probabilistic climate change projections for CO_2 stabilization profiles

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[1] Probabilistic projections of future climate change for a range of CO_2 stabilization profiles intended for the Fourth Assessment Report of the Intergovernmental Panel on Climate Change are presented. A very large ensemble of simulations with the reduced complexity, Bern2.5D climate model is used to explore the uncertainties in projected long-term changes in surface air temperature and sea level due to uncertainties in climate sensitivity and ocean heat uptake. Previously published probability density functions of climate sensitivity are used to calculate probabilistic projections for different CO_2 stabilization levels and to calculate the probability of not exceeding a certain global mean surface temperature for a given stabilization level. This provides a new way of communicating long-term uncertainty which can serve as a basis for selecting a CO_2 stabilization level given a temperature limit and help to estimate the overshoot risk society is willing to accept.
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1. Introduction

[2] Avoiding dangerous interference with the climate system requires atmospheric greenhouse gas concentrations to eventually be stabilized and anthropogenic emissions to be reduced substantially. For the upcoming Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC), we have released a series of updated profiles for stabilizing concentrations of equivalent CO_2 at different levels (http://www.climate.unibe.ch/emicAR4/). These scenarios are run with a perturbed physics ensemble of a climate model of intermediate complexity, allowing us to reflect model-physics uncertainty as well as permitting us to estimate changes on timescales exceeding the capacity of comprehensive models.

[3] Atmospheric CO_2 is prescribed directly in the idealized scenarios used here, other forcings are not considered. Even though this neglects socio-economic aspects and uncertainties in the pathway leading to stabilization [e.g., *Webster et al.*, 2003] as well as the effect of uncertainties in the marine [*Joos et al.*, 1999] and terrestrial [e.g., *Cox et al.*, 2000; *Joos et al.*, 2001] carbon cycles on the projections, projected climate change remains uncertain due to uncertainties in climate sensitivity and ocean heat uptake. Of the physical parameters, climate sensitivity (the equilibrium global mean surface warming for doubling preindustrial atmospheric CO_2) is the largest source of uncertainty and has proven difficult to constrain from present day climatology [*Murphy et al.*, 2004; *Stainforth et al.*, 2005]. Similarly, climate sensitivity is weakly constrained by the observed atmospheric and oceanic warming of the 20th century [*Andronova and Schlesinger*, 2001; *Forest et al.*, 2002; *Gregory et al.*, 2002; *Knutti et al.*, 2002]. Most studies find climate sensitivity ranges that exceed the canonical 1.5 to 4.5 K range estimated by *IPCC* [2001]. The 95% confidence level is above 10 K in some probability density functions for climate sensitivity. This implies the (albeit small) possibility for very large long-term warming. While climate sensitivity dominates the uncertainty in long-term surface warming, the warming and sea level rise over the next century or so is strongly affected by the rate of ocean heat uptake. The rate of heat uptake is difficult to constrain from models [*Forest et al.*, 2002; *Knutti et al.*, 2003] and observations are uncertain and relatively short [*Levitus et al.*, 2005].

2. Model and Ensemble Setup

[4] The newly developed stabilization profiles were constructed following *Enting et al.* [1994] and *Wigley et al.* [1996] using the most recent atmospheric CO_2 observations, CO_2 projections with the Bern Carbon Cycle-Climate model [*Joos et al.*, 2001] for the A1T scenario over the next few decades, and a Padé approximant (a ratio of two polynomials) [*Enting et al.*, 1994] leading to stabilization. The set of scenarios includes direct stabilization at levels of 450, 550, 650, 750 and 1000 ppm atmospheric CO_2 equivalent (SP450 to SP1000), two cases of delayed stabilization at 450 and 550 ppm (DSP450, DSP550) and two overshoot scenarios with subsequent stabilization at 350 and 450 ppm (OSP350, OSP450).

[5] The Bern2.5D climate model consists of a zonally averaged dynamic ocean, an energy-moisture balance atmosphere and a thermodynamic sea ice component [*Stocker et al.*, 1992] and is similar to the version used in previous global warming studies [*Knutti et al.*, 2002, 2003]. Radiative forcing of CO_2 is calculated by a simplified expression [*Myhre et al.*, 1998], and climate sensitivity can be adjusted by a feedback parameter representing all otherwise missing processes affecting surface temperature [*Knutti et al.*, 2003].

[6] The ensemble combines all scenarios with climate sensitivities from 0.5 to 10 K, with three different ocean mixing parameterizations, and with ocean vertical/diapycnal diffusivity set from 10^{-5} to 10^{-4} m^2/s. The ocean mixing parameterizations are horizontal/vertical diffusion (HOR), isopycnal/diapycnal diffusion (ISO), and isopycnal diffu-

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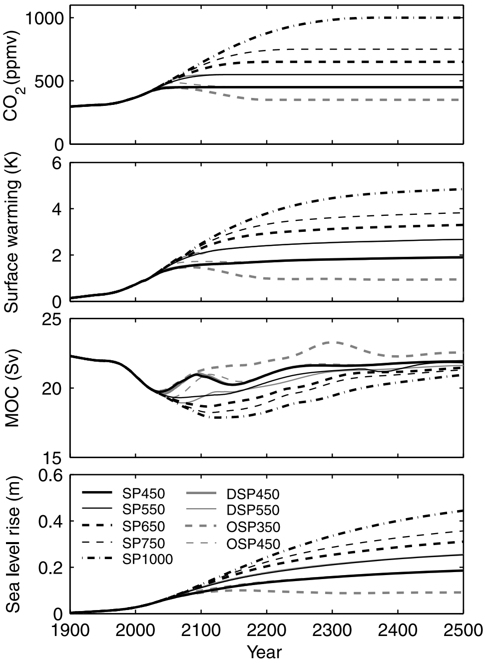

Figure 1. Overview of prescribed CO_2 profiles and the response in surface warming, Atlantic meridional overturning circulation (MOC) and steric sea level rise using the Bern2.5D climate model with a standard climate sensitivity of 3 K, horizontal/vertical mixing and vertical diffusivity of $5 \cdot 10^{-5}$ m^2/s. Atmospheric CO_2 concentration is stabilized at 450 ppmv (SP450), 550 ppmv (SP550), 650 ppmv (SP650), 750 ppmv (SP750) and 1000 ppmv (SP1000) for the standard cases. In addition, two delayed stabilizations to 450 and 550 ppm (DSP450 and DSP550) and two overshoot scenarios with subsequent stabilization at 350 and 450 ppm (OSP 350 and OSP 450) are considered. Anomalies in temperature and sea level are relative to preindustrial values throughout the paper.

sion with the Gent/McWilliams (GM) parameterization [*Knutti and Stocker*, 2000; *Knutti et al.*, 2000]. This parameter range results in broad agreement with hydrographic observations and leads to a total of 5400 simulations which allow for a comprehensive uncertainty analysis (see supplementary material[1] for details on the parameter ranges). In addition, scenarios with the same parameter combinations but idealized exponential CO_2 doubling/quadrupling at different increase rates are calculated.

3. Results

[7] An overview of the new stabilization profiles and the associated climate response is shown in Figure 1. Surface air temperature reaches equilibrium after a few hundred years, depending on the stabilization level. Adjustments of sea level have a much longer timescale, and sea level continues to rise even after year 3000, an important fact for the committed warming and sea level rise [*Meehl et al.*, 2005; *Wigley*, 2005]. However, sea level rise in this model only includes thermal expansion of the water, the total sea level would probably be about doubled due to melting of glaciers and ice caps and changes in groundwater storage [*IPCC*, 2001; *Wigley*, 2005]. The Atlantic meridional overturning circulation (MOC) decreases slightly but recovers to its control state after a few centuries. For higher climate sensitivities, the warming eventually results in a permanent shutdown of the circulation within about 300 years (not shown), causing an additional sea level rise of about 0.5 m, similar to previous studies with this model [*Knutti and Stocker*, 2000]. Simulations with different rates of CO_2 increase (not shown) also confirm the rate-dependent stability of the MOC [*Stocker and Schmittner*, 1997].

[8] The effect of delaying stabilization by about 20 years (DSP450 vs. SP450) has a comparably small overall effect on the climate response. Similarly, overshooting the stabilization target by 50 ppm CO_2 (or the equivalent radiative forcing thereof, OSP450 vs. SP450) for a few decades has a small impact on simulated global surface warming and results in an overshoot of only about 0.1 K due to the thermal inertia of the system. However, if the rate of change is important or if the system is close to a threshold, such delays or overshoots may have strong, possibly nonlinear impacts on the climate response. Furthermore, differences in the pathway leading to stabilization have important implications for allowed carbon emissions.

[9] While uncertainties have been studied quite extensively for the climate of the next century [*Knutti et al.*, 2002; *Stott and Kettleborough*, 2002; *Webster et al.*, 2003], only a few uncertainty estimates for long-term stabilization profiles are available so far [*O'Neill and Oppenheimer*, 2004; *Meinshausen*, 2005; *Wigley*, 2005]. For a probabilistic projection, we use the different ocean versions and published PDFs for climate sensitivity [*Andronova and*

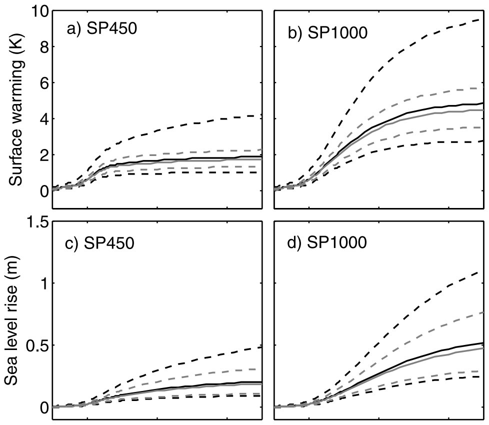

Figure 2. Median projections (solid) of surface warming (top) and steric sea level rise (bottom) for the stabilization profiles SP450 (left) and SP1000 (right). Dashed lines show the 5 to 95% uncertainty range, taking into account 30 different ocean mixing versions and the uncertainty in climate sensitivity. Black lines show the projection when giving equal weight to all published PDFs of climate sensitivity (see supplementary material). Grey lines show a more optimistic case where the 1.5 to 4.5 K sensitivity range is assumed to be the 90% confidence range of a log-normal distribution.

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[1] Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2005GL023294.

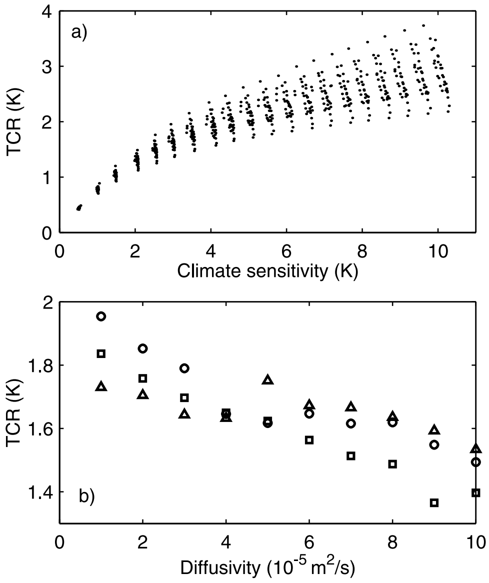

Figure 3. a) Transient climate response (TCR, global mean surface warming at CO_2 doubling in a 1%/yr scenario) versus climate sensitivity for all ocean mixing parameterizations. Each point represents an individual model simulation. Climate sensitivity is adjusted through a feedback parameter on global temperature. b) TCR versus vertical/diapycnal ocean diffusivity for ten diffusivities and horizontal diffusion (HOR, circles), isopycnal diffusion (ISO, squares) and the Gent/McWilliams mixing (GM, triangles) and for climate sensitivity set to 3 K.

Schlesinger, 2001; *Wigley and Raper*, 2001; *Forest et al.*, 2002; *Gregory et al.*, 2002; *Knutti et al.*, 2002; *Murphy et al.*, 2004] (see supplementary material). The median and 5 to 95% confidence range for surface warming and sea level rise obtained by this method are shown in Figure 2 for a low (SP450) and a high (SP1000) stabilization profile (black lines). The projection uncertainties close to equilibrium are large and reflect the large uncertainty in climate sensitivity. In particular, the high values of climate sensitivity found to be consistent with observations in some studies cause the 95% confidence limit to be more than twice as large as the median. If the climate sensitivity range is assumed to be log-normal and covering 90% of the 1.5 to 4.5 K range given by *IPCC* [2001], as suggested by *Wigley and Raper* [2001], the projection uncertainties are reduced (Figure 2, grey lines) and the very high values can be excluded. Note that all profiles are calculated to year 5000 to estimate the equilibrium response.

[10] The transient uncertainty is smaller than the equilibrium uncertainty. Additional simulations with idealized CO_2 increase of 1%/yr show a nonlinear relationship between the transient climate response (TCR, the warming at CO_2 doubling in a 1%/yr scenario) and climate sensitivity (Figure 3a). Thus, TCR is easier to constrain than sensitivity, in particular its upper end. For constant sensitivity, higher TCR is obtained for ocean model versions with smaller vertical mixing parameterized as vertical diffusivity (Figure 3b). A higher diffusivity in the ocean leads to a increased transient heat uptake during the early phase of the warming, and thus dampens the atmospheric warming to radiative forcing.

[11] An upper limit on warming and sea level rise requires stabilization (or peaking) of atmospheric CO_2 and radiative forcing at some level. The choice of that level depends in the first place on the target to meet. In the reduced complexity model, we define as target that global mean surface warming does not exceed an upper limit. Since the climate response for a specific scenario is uncertain, the choice will also depend on the acceptable risk. Here, the risk is the probability that the realized warming will be larger than the specified limit (we recognize that the common definition of risk is probability times consequence and treat all climate change as having equal consequence here). For any combination of temperature limit and CO_2 stabilization level, the risk can be derived from the PDFs of equilibrium temperature for each stabilization level. We summarize the results here by calculating the probability of remaining below a certain temperature limit given a stabilization level of CO_2. Figure 4 shows the composite when using all published PDFs of climate sensitivity and assuming the more narrow sensitivity range approximately covering the IPCC range [*Wigley and Raper*, 2001], respectively. The nomenclature and probability ranges are taken from *IPCC* [2001]. As an example, keeping global mean surface warming below 2 K relative to preindustrial is a target recently put forward by some nations, scientists and environmental organizations.

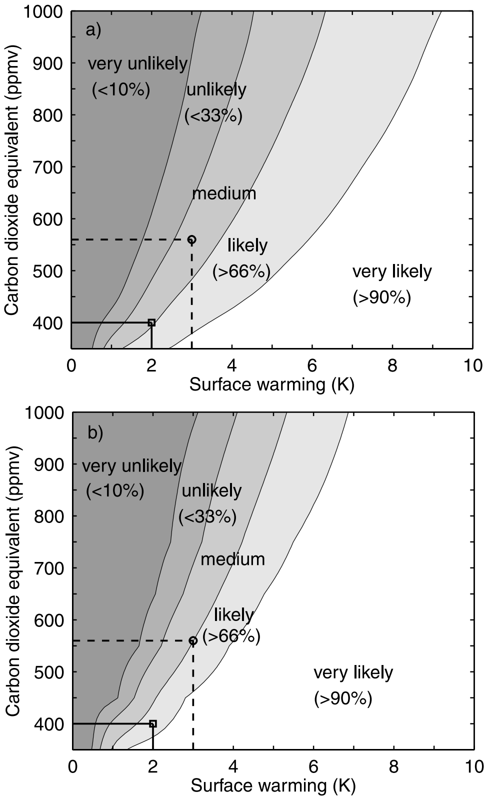

Figure 4. Probability of staying below a certain equilibrium global mean surface warming for a given stabilization value of atmospheric CO_2 (or the equivalent radiative forcing thereof), for a) all published climate sensitivity PDFs and b) for the more optimistic case where the 1.5 to 4.5 K sensitivity range is assumed to be the 90% confidence range of a log-normal distribution. The probability terminology follows *IPCC* [2001].

Considering all sensitivity PDFs (Figure 4a), stabilizing atmospheric concentrations at 400 ppm CO_2 equivalent (solid lines, square) is just at the edge of 'likely' restricting the warming to less than 2 K. A more relaxed target of staying below 3 K warming cannot be considered 'likely' for doubling preindustrial CO_2 (dashed lines, circle). For a more narrow range of sensitivity (Figure 4b), our confidence increases to reach these targets. Given an appropriate model, any other metrics of dangerous interference with the climate, of impacts or of costs of climate change could be used to define targets in such a framework instead of the 2 K threshold. But different targets might require different ensemble weighting strategies [*Frame et al.*, 2005].

4. Conclusions

[12] A multi thousand member ensemble of stabilization simulations and PDFs of climate sensitivities was used to generate probabilistic projections of temperature and steric sea level rise. Uncertainties related to ocean mixing mainly affect the transient climate response and long-term sea level rise, while uncertainties in climate sensitivity dominate the long-term response in both surface warming and sea level rise. A new way of presenting stabilization targets in a probabilistic way illustrates that the choice of a future emission path does not only depend on the agreed limits of warming, but also on the accepted risk of exceeding these limits. The more certainty is required about not exceeding a limit, the lower the stabilization level must be. Whatever assumptions are used, a goal of not exceeding a global mean surface warming of for example 2 K is ambitious and requires stabilization well below doubling of preindustrial CO_2 equivalent. Therefore, large emission reductions are unavoidable to reach such a goal.

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