Correlation between climate sensitivity and aerosol forcing and its implication for the "climate trap"

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Abstract

Climate sensitivity and aerosol forcing are dominant uncertain properties of the global climate system. Their estimates based on the inverse approach are interdependent as historical temperature records constrain possible combinations. Nevertheless, many literature projections of future climate are based on the probability density of climate sensitivity and an independent aerosol forcing without considering the interdependency of such estimates. Here we investigate how large such parameter interdependency affects the range of future warming in two distinct settings: one following the A1B emission scenario till the year 2100 and the other assuming a shutdown of all greenhouse gas and aerosol emissions in the year 2020. We demonstrate that the range of projected warming decreases in the former case, but considerably broadens in the latter case, if the correlation between climate sensitivity and aerosol forcing is taken into account. Our conceptual study suggests that, unless the interdependency between the climate sensitivity and aerosol forcing estimates is properly considered, one could underestimate a risk involving the “climate trap”, an unpalatable situation with a high climate sensitivity in which a very drastic mitigation may counter-intuitively accelerate the warming by unmasking the hidden warming due to aerosols.

1. Introduction

Humans disturb the climate in two counteracting ways. On the one hand greenhouse gas (GHG) emissions lead to a warming by enhanced absorption of terrestrial radiation. On the other hand anthropogenic aerosols (except for black carbon) induce a cooling by scattering more solar radiation back to space, a process enhanced by interactions of aerosols with clouds. The combined effect of GHGs and aerosols mainly defines the total anthropogenic radiative forcing and hence the impact of human activities on the global climate. The current radiative forcing of anthropogenic GHGs is estimated to be about 2.9 W/m^2 with a high level of scientific understanding (IPCC 2007, p.200), whereas the radiative forcing due to anthropogenic aerosols is highly uncertain (−0.5 to −2.2 W/m^2 (only the first indirect effect)) (IPCC 2007, p.200). Accordingly, the total forcing arising from human activities is very uncertain in magnitude (0.6 to 2.4 W/m^2) (IPCC 2007, p.200), as it is mainly the result of these two opposing mechanisms.

This large uncertainty in the current and historical forcing affects the assessment of climate sensitivity (CS), which is commonly defined as the equilibrium global mean temperature response to a doubling of the atmospheric CO_2 concentration from the pre-industrial level (excluding very long-term processes, e.g. ice sheet melting). CS is estimated either by perturbing coupled atmosphere/ocean general circulation models (AOGCMs) or by relating changes in observed and reconstructed global temperature with historical radiative forcing (based mostly on simple climate models, SCMs). Both methods indicate that CS is likely in the range 2°C - 4.5°C per doubling of atmospheric CO_2 concentration (IPCC 2007, pp.798-799; Knutti and Hegerl 2008). However, there is a considerable probability of exceeding the upper bound of this range (e.g. IPCC 2007, pp.798-799; Roe and Baker 2007; Knutti and Hegerl 2008; Tanaka et al. 2009b). A high estimate of CS implies a small total forcing and thus a strong anthropogenic aerosol forcing (AF) (e.g. Harvey and Kaufmann 2002; Andreae et al. 2005; Chylek et al. 2007; Knutti 2008; Tanaka et al. 2009b; Armour and Roe 2011; Johansson 2011), as the observed global temperature trend of the last century (in particular, the warming of the second half of the last century, which cannot be explained by natural variability alone (IPCC 2007, pp.702-703 and p.727)) would otherwise be overestimated.

Another interesting feature of the two opposing forcing mechanisms is the marked difference in their timescale (IPCC 2007, p.203). Most of the GHGs stay in the atmosphere for many years, whereas aerosols are removed from the troposphere within days. Therefore, a rapid reduction in all emissions, i.e. a large-scale phase-out of fossil fuel combustion, would almost instantly eliminate the AF, leaving the remnant long-lived GHG forcing. In the following decades this could counter-intuitively increase the total forcing in comparison to a scenario with steadily increasing emissions (Wigley 1991; Hare and Meinshausen 2006), in particular, if the aerosol cooling effect is strong. An AOGCM study shows that an instant removal of all anthropogenic sulfate aerosols from the atmosphere could even increase the global temperature by about 0.8°C in the years thereafter (Brasseur and Roeckner 2005; IPCC 2007, p.567).

In sum, a high CS implies a strong anthropogenic AF because of the historical constraints, resulting in a pronounced warming in the future, which will even accelerate after an aerosol emission reduction. The interrelation of CS and AF estimates affects the risk of a dangerously strong global warming. However, it has not been explored much yet how the CS-AF interdependency influences the range of future warming.

The interdependency between CS and AF estimates constrained by historical observations is treated differently across models as summarized below:

- SCMs: While such a correlation between CS and AF is taken into account in several studies for future warming (e.g. Forest et al. 2002; Knutti et al. 2002; Frame et al. 2005; Meinshausen et al. 2009; Sokolov et al. 2009; Tanaka et al. 2009b; Urban and Keller 2010; Armour and Roe 2011; Johansson 2011), it is ignored by others (e.g. IPCC 2001; Wigley and Raper 2001; Caldeira et al. 2003; Hare and Meinshausen 2006; IPCC 2007; Rive et al. 2007; Ramanathan and Feng 2008; Penner et al. 2010). In IPCC TAR (2001, p.577), the range of future warming has been estimated by using SCMs without considering the interdependency between CS and AF estimates – SCM parameters including CS are tuned to emulate several AOGCMs, but the AF is not adjusted when the SCMs simulate future climate. In IPCC AR4 (2007, p.810 and p.844), SCMs are used only to supplement AOGCM runs, but the same problem persists.
- AOGCMs: It has been shown that there is an inverse relationship between the CS and AF estimates in AOGCMs (Kiehl 2007; Knutti 2008) even though CS and AF emerge from physical parameterizations and data independently from each other. The negative correlation between CS and AF values explains why most of the AOGCMs well reproduce the historical observed warming (Kerr 2007; Kiehl 2007; Schwarz et al. 2007; Knutti 2008) although their CS estimates differ by a factor of two (IPCC 2007, p.631) and the total forcing is also different (e.g. some AOGCMs do not have the indirect aerosol effect).

In spite of the different treatments of the CS-AF interdependency among the studies, only a few studies (Andreae et al. 2005; Knutti 2008) have investigated how such an interrelation influences the range of projected future warming . Andreae et al. (2005) is the first study that specifically addressed this issue. Knutti (2008) took a step further and showed how much the interdependency between CS and AF reduces the uncertainty range of future warming over time, given three different correlation strengths. However, these studies explored this issue only under business-as-usual scenarios without pursuing it further under mitigation scenarios involving a rapid SO_2 emission reduction – the estimate of the short-term warming triggered by a drastic SO_2 abatement can be strongly influenced by the correlation between CS and AF.

Thus, the conceptual study presented here aims at illustrating the importance of the interdependency between the estimates of uncertain climate parameters for projections of the future climate. To be as illustrative as possible we compare two drastically different emission scenarios for the 21st century: A business-as-usual scenario and a shutdown of all emissions (both GHGs and aerosols) in the year 2020. In terms of socio-economic constraints the latter scenario is not realistic, but it displays a geophysical limit of the effects that a fast emission reduction could have, as termed "geophysical commitment" by Hare and Meinshausen (2006).

The latter case involving an emission shutdown also contributes to the discussion related to the zero emissions commitment (Hare and Meinshausen 2006; IPCC 2007 p.567; Plattner et al. 2008; Solomon et al. 2009; Frölicher and Joos 2010; Matthews and Weaver 2010; Armour and Roe 2011). The initial abrupt warming induced by a cessation of the aerosol forcing, which can be considered as "hidden commitment" as a measure for the committed warming masked by aerosols, has received little attention in the climate commitment studies with Armour and Roe (2011) being an exception. No climate commitment study has explicitly shown how the aerosol-led rapid warming is affected by the CS and AF interdependency, which we explore here.

2. Methodology

The Aggregated Carbon Cycle, Atmospheric Chemistry, and Climate model (ACC2) (Tanaka et al. 2007; Tanaka 2008; Tanaka et al. 2009a,b) describes major physical and biogeochemical processes within the Earth system on a global-annual-mean level. The most relevant part of ACC2 is the climate component: Diffusion Ocean Energy Balance Climate model (DOECLIM) (Kriegler 2005; Tanaka et al. 2007, Section 2.3), which is a land-ocean energy balance model coupled with a heat diffusion model to describe heat transfer to the interior ocean. The limitation in spatial and temporal resolution allows an inversion of ACC2, i.e. the concurrent optimization of model parameters and the simulated time evolution of the coupled climate - carbon cycle system. In this optimization, the value of a cost function is minimized; that is, the sum of the squared deviations of parameter values and data from their apriori values weighted by their uncertainty (equation (1) of Tanaka et al. (2009b)). Data are time series of atmospheric CO_2, CH_4, and N_2O concentration, ocean and land CO_2 uptake, and global temperature change (Tanaka 2008, Table 3.1). Parameters include the β-factor (CO_2 fertilization) and the CS (Tanaka 2008, Table 3.2). Parameters with annual values are the CO_2, CH_4, and N_2O emissions and the "missing forcing" (Tanaka et al. 2009b; discussed later). For the sake of analysis, no climate-carbon cycle feedbacks are provided – i.e. carbon cycle processes are assumed to be insensitive to temperature changes. We also assume a fixed estimate of ocean diffusivity (0.55 cm^2/s based on Kriegler (2005)). The sensitivity of our results to this assumption is discussed later.

In our model setup, the total forcing is given as the sum of three types of forcing (Tanaka 2008, Fig. A.6; Tanaka et al. 2009b, Fig. 2): i) calculated radiative forcing subject to uncertainties (CO_2, CH_4, and N_2O forcing), ii) prescribed/parameterized radiative forcing without uncertainties (other GHGs (e.g. ozone), aerosol, volcanic, solar forcing), and iii) missing forcing (Tanaka et al. 2009b). The third term represents the noise in the temperature record induced by internal climate variability and the uncertainty in prescribed or parameterized radiative forcing, which is mostly the uncertainty in AF. Types of forcing that are not included in the model (e.g. albedo forcing due to land use (-0.20 ± 0.20 W/m^2 (IPCC 2007, p.204)) and mineral dust forcing (-0.10 ± 0.20 W/m^2, (IPCC 2007, p.204)) are also accounted for in the missing forcing. Note that the efficacy of forcing (Hansen et al. 2005) is not considered in the analysis here – i.e. it is assumed that CS is the same for all the forcing terms.

The simulations performed for this study are done in two steps: First, inversions of ACC2 are performed for the period 1750-2000 with fixed values of CS (2°C, 3°C, 5°C, and 10°C). 3°C is the most likely estimate for the climate sensitivity among others (IPCC 2007, pp.798-799) while the estimate of 10°C is the least likely. Second, forward runs of ACC2 are done for the 21st century with parameters as derived by the inversions of the historical period and emissions specified by the SRES A1B scenario (IPCC 2000). This is a business-as-usual scenario with maximum GHG emissions in the middle of the 21st century. All these future runs are repeated with a modification in the emission scenario. From the year 2020 on they are performed with the theoretically most drastic emission reduction – a shutdown of all emissions (both GHGs and aerosols).

In all the future simulations, the base AF is scaled to the common estimate of −1.3 W/m^2 in the year 2000 by parameterizing with the emissions of SO_2 as well as carbon monoxide (a surrogate for carbonaceous aerosols) (Joos et al. 2001; Tanaka 2008, Table 2.1). The average missing forcing determined by each ACC2 inversion for the historical period provides a correction for this base AF magnitude so that it is consistent with the predefined CS. Under the assumption that the missing forcing averaged over the latter half of the 20th century mostly reflects the uncertainty in AF, the base AF throughout the 21st century is scaled with the factor 1 + missing forcing (averaged 1950-2000) / AF (averaged 1950-2000). Thus, after the year 2000 the corrected AF is reduced in magnitude for a small CS and increased for a high CS (Fig. 1a). Scaling the AF also in the historical period (rather than using the missing forcing) would be more straightforward, but such an approach could lead to a bias in the estimates of CS and AF (Tanaka et al. 2009b).

Additionally, simulations are conducted to show how much the projections of future climate are distorted, if the interdependency in the estimates of CS and AF is neglected. The runs with a CS of 2°C, 5°C, and 10°C per doubling of atmospheric CO_2 concentration are repeated for the period 2000-2100, but with the AF, parameter values (β-factor, etc.), and initial state (in the year 2000) set as in the future run with the CS of 3°C. These climate projections disregard any relation in the estimates of CS and other climate parameters and are therefore called "separate" hereafter (in contrast to the "interdependent" runs).

3. Results

For the period 1750-2000 the ACC2 inversions result in a good fit of the data for all the prescribed CS varied in the range of 2 - 10°C (see the radiative forcing and temperature projections in Tanaka et al. (2009b, Fig. 2 (missing forcing approach)). The warming till the year 2000 differs slightly by 0.10°C with CS (0.68°C warming since pre-industrial in the case of CS=2°C; 0.78°C warming in the case of CS=10°C). The magnitude of total AF in year 2000 (to be used for future runs) is estimated to be -1.04, -1.32, -1.57, and -1.78 W/m^2 for CS=2, 3, 5, and 10°C, respectively, the range of which is narrower than the AF uncertainty shown in IPCC (2007, p.200). These values are compatible with the relationship between CS and AF reported by Andreae et al. (2005, Fig. 1).

On this basis, the global temperature evolution of the 21st century is simulated in the interdependent runs with different prescribed values of CS (Fig. 1b). In the case of an emission shutdown in 2020, the warming is accelerated in the years thereafter for all prescribed CS values. However, the rate of this warming is strongly dependent on the CS and is as high as 0.32°C/decade for CS=2°C and 1.17°C/decade for CS=10°C (Fig. 1c).

A maximum in global temperature is reached 5 to 30 years after the emission shutdown and is 1.17 - 2.81°C above the pre-industrial level. Most of this large spread in the estimated global warming emerges after the emission shutdown. The temperature increases only by 0.24°C for CS=2°C, but jumps up by 1.36°C for CS=10°C (Fig. 1b). This dependence of the post-shutdown warming on the CS is much weaker in the separate simulations. The warming after 2020 amounts to 0.34°C for CS=2°C and 1.00°C for CS=10°C (Fig. 2a).

Forcing ACC2 with the continuous evolving emissions results in a more gradual increase of the global temperature (Fig. 1b). Nevertheless, the simulated warming is very different with respect to the presumed value of CS and amounts to 2.40 - 6.90°C in the year 2100. This range is larger for the separate runs (2.33 - 7.38°C) (Fig. 2b). The rate of warming is highest in the middle of the 21st century coincident with the largest GHG emissions. For the interdependent runs it ranges from 0.26°C/decade for CS=2°C to 0.84°C/decade for CS=10°C.

All these results are based on an ocean diffusivity of 0.55 cm^2/s. Simulation results with higher estimates of 1.0 and 2.0 cm^2/s (error bars of Fig. 2) do not influence the findings discussed in this article.

4. Discussion

Accounting for the interdependency between CS and AF estimates changes the expectations about future warming considerably. This is most prominent for a drastic reduction of emissions in the near future (Fig.

2a). In this case the uncertainty in the projections of future climate is enhanced by the CS-AF interdependency – the spread in the anticipated warming after a shutdown of all emissions in the year 2020 nearly doubles by including the CS-AF interrelation in our simulations. An explanation for this difference between the interdependent and separate simulations can be directly inferred from the cause of the sudden warming after the emission shutdown – the instant cessation of AF. The abrupt increase in the total forcing varies in the interdependent runs from 1.01 W/m² for CS=2°C to 1.97 W/m² for CS=10°C, whereas it is the same for all separate simulations (1.37 W/m²). The total forcing change is predominantly ascribed to the cessation of AF, the strength of which is -1.37 W/m² for CS=2°C and -2.33 W/m² for CS=10°C in the interdependent cases and -1.72 W/m² in all the separate cases. The rest of the change in the total forcing is mostly explained by the concurrent drop of the tropospheric ozone forcing. Neglecting the CS-AF correlation diminishes the difference in radiative forcing before zero emissions and narrows the range of warming immediately following zero emissions.

A SCM-based study of Armour and Roe (2011) shows a maximum warming of 0.9°C immediately after an emission shutdown at the present-day condition (GHGs and aerosols), which is smaller than the upper range of the peak warming (1.36°C) after the 2020 emission shutdown that we obtained for the interdependent case. This is mainly because there is a greater aerosol forcing in 2020 than at present, resulting in a larger jump in forcing under zero emissions. The post-emission shutdown warming can be even more striking if an emission shutdown is assumed at the time of higher SO_2 emissions. AOGCM-based studies show a variety of responses upon emission shutdowns. The 0.8°C warming shown by an AOGCM study of Brasseur and Roeckner (2005) (also in IPCC (2007 p.567)) after a hypothetical removal of the entire burden of anthropogenic sulphate aerosols in 2000 is larger than what would be expected from our results for the model's CS of 3.4°C (IPCC 2007, p.631). On the other hand, the warming generated by another AOGCM study (CS of 2.0°C) (Frölicher and Joos 2010) after an emission shutdown (both GHGs and aerosols) is too small to be distinguished from the background natural variability.

Note that, after the emission shutdown, the warming persists for a long time owing to the slow decays of the atmospheric burden of long-lived GHGs (e.g. CO_2 and SF_6) (Mackenzie and Lerman 2006; Archer et al. 2009) and heat storage in the deep ocean (Plattner et al. 2008; Solomon et al. 2009; Frölicher and Joos

2010; Matthews and Weaver 2010; Solomon et al. 2010; Armour and Roe 2011). The slow drawdown of CO_2 following zero emissions results in an even slower reduction in forcing due to the logarithmic relationship between forcing and concentration. The difference in the warming levels in the separate and interdependent cases for the same CS eventually diminishes because the total radiative forcing is the same after the emission shutdown (Fig. 1a).

By contrast, in the case that follows the A1B scenario until 2100, the spread in global temperature is slightly smaller for the interdependent runs than for the separate ones (Fig. 2b). This result can be explained by the ongoing SO_2 emissions throughout the 21st century, which in the interdependent simulations are translated into different AFs depending on the presumed value of CS. This results in a larger aerosol cooling for a high CS than for a low CS, keeping the temperature curves closer together, whereas the AF is the same in all separate simulations. This finding is in line with Andreae et al. (2005), which however cannot be compared directly with our results due to several differences in the experimental setups. Our finding is also consistent with Knutti (2008), which shows that the range of future warming is smaller with a stronger negative correlation between CS and the total forcing.

Therefore, without the interdependency between CS and AF estimates taken into account, the range of future warming is overestimated when SO_2 emissions persist, whereas it is underestimated when SO_2 emissions cease. One may argue that the CS-AF interrelation is not very important because the SO_2 emissions in SRES are low toward the end of the 21st century (e.g. Wigley and Raper 2001) or that it is less relevant for studies using the newest RCP scenarios (Moss et al. 2010), in which SO_2 emissions are reduced faster than in SRES. Irrespective of the scenario, we believe that the CS-AF interdependency deserves more attention because it potentially influences the range of future warming substantially in a distinct way.

Our results provide the following implications for SCM and AOGCM studies:

- SCMs: As have been done in recent studies cited earlier, it is necessary to include the CS-AF interdependency in the projections of future climate to remove the bias that could otherwise be added. The ignorance of the CS-AF interdependency has led to an overestimation in the range of future warming under business-as-usual scenarios in many SCM-based studies including IPCC (2001, p.577; 2007, p.810 and p.844). However, it should be noted that in the case of IPCC such a bias is overshadowed by an opposite bias introduced by the limited range of climate sensitivity considered (Knutti et al. 2008; Armour and Roe 2011).

- AOGCMs: Many more parameters are involved and not all of them are tuneable against observations (Bender 2008), but it would be instructive to attempt a more systematic parameter tuning (rather than the uncoordinated approach typically taken) – it should ideally be not separately for CS and AF (e.g. Murphy et al. 2004; Haerter et al. 2009) but simultaneously for CS and AF.

Furthermore, our illustration shows that, with the large spread in the interdependent simulations after the emission shutdown, the global temperature overshoots the common climate policy target of 2°C warming in the case of CS>5°C. Furthermore, the rate of warming after an emission shutdown exceeds another common target of 0.2°C/decade even with a small CS.

5. Concluding remarks: "climate trap"

Overall, our analysis shows that in the case of a high CS (≈ 5°C) an unpalatable situation may already emerge in the next two decades. In the face of an accelerating warming, a rapid emission reduction would result in a large abrupt warming. Once being in this "climate trap", it would be impossible to keep the two most common climate policy targets by solely reducing emissions. Either the global temperature would exceed the limit of 2°C above the pre-industrial level driven by continued emissions, or the rate of warming would be much higher than 0.2°C/decade during the time of rapid emission reduction (Fig. 1). Under the emissions scenario we assume, such a dilemma situation could be reached at a warming level of about 1.2°C above the pre-industrial level. Our study is illustrative in nature, calling for more detailed studies to explore further this problem by using spatially-explicit models under socio-economically more elaborated emissions scenarios. Ways in which undesirable consequences can be avoided in such a situation should also be investigated.

References

Andreae MO, Jones CD, Cox PM (2005) Strong present-day aerosol cooling implies a hot future. Nature 435:1187-1190. doi: 10.1038/nature03671

Archer D, Eby M, Brovkin V, Ridgwell A, Cao L, Mikolajewicz U, Caldeira K, Matsumoto K, Munhoven G, Montenegro A, Tokos K. (2009) Atmospheric lifetime of fossil fuel carbon dioxide. Annu Rev Earth Planet Sci 37:117-134. doi: 10.1146/annurev.earth.031208.100206

Armour KC, Roe GH (2011) Climate commitment in an uncertain world. Geophys Res Lett 38:L01707. doi: 10.1029/2010GL045850

Bender FA-M (2008) A note on the effect of GCM tuning on climate sensitivity. Environ Res Lett 3:014001. doi: 10.1088/1748-9326/3/1/014001

Brasseur GP, Roeckner E (2005) Impact of improved air quality on the future evolution of climate. Geophys Res Lett 32:L23704. doi: 10.1029/2005GL023902

Caldeira K, Jain A, Hoffert M (2003) Climate sensitivity uncertainty and the need for energy without CO_2 emission. Science 299:2052-2054. doi: 10.1126/science.1078938

Chylek P, Lohmann U, Dubey M, Mishchenko M, Kahn R, Ohmura A (2007) Limits on climate sensitivity derived from recent satellite and surface observations. J Geophys Res 112:D24S04. doi: 10.1029/2007JD008740

Frölicher TL, Joos F (2010) Reversible and irreversible impacts of greenhouse gas emissions in multi-century projections with the NCAR global coupled carbon cycle-climate model. Clim Dyn 35:1439-1459. doi: 10.1007/s00382-009-0727-0

Forest CE, Stone PH, Sokolov AP, Allen MR, Webster MD (2002) Quantifying uncertainties in climate system properties with the use of recent climate observations. Science 295:113-117. doi: 10.1126/science.1064419

Frame DJ, Booth BBB, Kettleborough JA, Stainforth DA, Gregory JM, Collins M, Allen MR (2005) Constraining climate forecasts: The role of prior assumptions. Geophys Res Lett 32:L09702. doi: 10.1029/2004GL022241

Haerter JO, Roeckner E, Tomassini L, von Storch J-S (2009) Parametric uncertainty effects on aerosol radiative forcing. Geophys Res Lett 36:L15707. doi: 10.1029/2009GL039050

Hansen J et al. (2005) Efficacy of climate forcings. J Geophys Res 110:D18104. doi: 10.1029/2005JD005776

Hare B, Meinshausen M (2006) How much warming are we committed to and how much can be avoided? Clim Change 75:111-149. doi: 10.1007/s10584-005-9027-9

Harvey LDD, Kaufmann RK (2002) Simultaneously constraining climate sensitivity and aerosol radiative forcing. J Climate 15:2837–2861. doi: 10.1175/1520-442(2002)015%3C2837:SCCSAA%3E2.0.CO;2

IPCC (2000) Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change, edited by N. Nakićenović and R. Swart, Cambridge Univ. Press, U.K.

IPCC (2001) Climate change 2001: the scientific basis. Contribution of working group I to the third assessment report of the intergovernmental panel on climate change. In: Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Dai X, Maskell K, Johnson CA (eds) Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881 pp

IPCC (2007) Climate change 2007: the physical science basis. contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp

Johansson D (2011) Temperature stabilization, ocean heat uptake and radiative forcing overshoot profiles. Clim Change 108:107-134. doi: 10.1007/s10584-010-9969-4

Joos F, Prentice C, Sitch S, Meyer R, Hooss G, Plattner G-K, Gerber S, Hasselmann K (2001) Global warming feedbacks on terrestrial carbon uptake under the Intergovernmental Panel on Climate Change (IPCC) emission scenarios. Glob Biogeochem Cycles 15:891-907. doi: 10.1029/2000GB001375

Kerr RA (2007) Another global warming icon comes under attack. Science 317:28-29. doi: 10.1126/science.317.5834.28a

Kiehl JT (2007) Twentieth century climate model response and climate sensitivity. Geophys Res Lett 34:L22710. doi: 10.1029/2007GL031383

Knutti R, Stocker TF, Joos F, Plattner G-K (2002) Constraints on radiative forcing and future climate change from observations and climate model ensembles. Nature 416:719-723. doi: 10.1038/416719a

Knutti R (2008) Why are climate models reproducing the observed global surface warming so well? Geophys Res Lett 35:L18704. doi: 10.1029/2008GL034932

Knutti R, Hegerl GC (2008) The equilibrium sensitivity of the Earth's temperature to radiation changes. Nature Geoscience 1:735-743. doi: 10.1038/ngeo337

Knutti R, Allen MR, Friedlingstein P, Gregory JM, Hegerl GC, Meehl GA, Meinshausen M, Murphy JM, Plattner G-K, Raper SCB, Stocker TF, Stott PA, Teng H, Wigley TML (2008). A review of uncertainties in global temperature projections over the twenty-first century. J Climate 21:2651–2663. doi: 10.1175/2007JCLI2119.1

Kriegler E (2005) Imprecise probability analysis for integrated assessment of climate change. PhD dissertation, Potsdam Universität, 258 pp. http://www.pik-potsdam.de/~kriegler/

Mackenzie FT, Lerman A (2006) Carbon in the geobiosphere: earth’s outer shell. Springer, Dordrecht, The Netherlands, 402 pp

Matthews HD, Weaver AJ (2010) Committed climate warming. Nature Geoscience 3:142 – 143. doi: 10.1038/ngeo813

Meinshausen, M. et al. (2009) Greenhouse-gas emission targets for limiting global warming to 2°C. Nature 458:1158-1162. doi: 10.1038/nature08017

Moss RH et al. (2010) The next generation of scenarios for climate change research and assessment. Nature 463:747-756. doi: 10.1038/nature08823

Murphy JM, Sexton DMH, Barnett DN, Jones GS, Webb MJ, Collins M, Stainforth DA (2004) Quantifying uncertainty in model predictions. Nature 430:768-772. doi: 10.1038/nature02771

Penner JE, Prather MJ, Isaksen ISA, Fuglestvedt JS, Klimont Z, Stevenson DS (2010) Short-lived uncertainty? Nature Geoscience 3:587-588. doi: 10.1038/ngeo932

Plattner G-K et al. (2008) Long-term climate commitments projected with climate–carbon cycle models. J Climate 21:2721–2751. doi: 10.1175/2007JCLI1905.1

Ramanathan V, Feng Y (2008) On avoiding dangerous anthropogenic interference with the climate system: Formidable challenges ahead. PNAS 105:14245-14250. doi: 10.1073/pnas.0803838105

Rive N, Torvanger A, Berntsen T, Kallbekken S (2007) To what extent can a long-term temperature target guide near-term climate change commitments? Clim Change 82:373-391. doi: 10.1007/s10584-006-9193-4

Roe GH, Baker MB (2007) Why is climate sensitivity so unpredictable? Science 318:629-632. doi: 10.1126/science.1144735

Schwartz SE, Charlson RJ, Rodhe H (2007) Quantifying climate change — too rosy a picture? Nature Reports Clim Change 2:23-24. doi: 10.1038/climate.2007.22

Sokolov AP, Stone PH, Forest CE, Prinn R, Sarofim MC, Webster M, Paltsev S, Schlosser CA, Kicklighter D, Dutkiewicz S, Reilly J, Wang C, Felzer B, Melillo JM, Jacoby HD (2009) Probabilistic Forecast for Twenty-First-Century Climate Based on Uncertainties in Emissions (Without Policy) and Climate Parameters. J Climate 22:5175-5204. doi: 10.1175/2009JCLI2863.1

Solomon S, Plattner G-K, Knutti R, Friedlingstein P (2009) Irreversible climate change due to carbon dioxide emissions. PNAS 106:1704–1709. doi: 10.1073/pnas.0812721106

Solomon S, Daniel JS, Sanford TJ, Murphy DM, Plattner G-K, Knutti R, Friedlingstein P (2010) Persistence of climate changes due to a range of greenhouse gases. PNAS 107:18354-18359. doi: 10.1073/pnas.1006282107

Tanaka K, Kriegler E, Bruckner T, Hooss G, Knorr W, Raddatz T (2007) Aggregated carbon cycle, atmospheric chemistry, and climate model (ACC2): description of the forward and inverse modes. Reports on earth system science, no 40. Max Planck Institute for Meteorology, 188 pp. http://www.mpimet.mpg.de/wissenschaft/publikationen/erdsystemforschung.html

Tanaka K (2008) Inverse estimation for the simple earth system model ACC2 and its applications. PhD dissertation, Hamburg Universität, International Max Planck Research School on Earth System Modelling, Hamburg, 296 pp. http://www.sub.uni-hamburg.de/opus/volltexte/2008/3654/

Tanaka K, O'Neill BC, Rokityanskiy D, Obersteiner M, Tol RSJ (2009a) Evaluating Global Warming Potentials with historical temperature. Clim Change 96:443- 466. doi: 10.1007/s10584-009-9566-6

Tanaka K, Raddatz T, O'Neill BC, Reick CH (2009b) Insufficient forcing uncertainty underestimates the risk of high climate sensitivity. Geophys Res Lett 36:L16709. doi: 10.1029/2009GL039642

Urban NM, Keller K (2010) Probabilistic hindcasts and projections of the coupled climate, carbon cycle and Atlantic meridional overturning circulation system: a Bayesian fusion of century-scale observations with a simple model. Tellus A 62:737-750. doi: 10.1111/j.1600-0870.2010.00471.x

Wigley TML (1991) Could reducing fossil-fuel emissions cause global warming? Nature 349:503-506. doi: 10.1038/349503a0

Wigley TML, Raper SCB (2001) Interpretation of high projections for global-mean warming. Science 293:451-454. doi: 10.1126/science.1061604

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Figure Captions

Figure 1. Total forcing (a), warming since pre-industrial (b), and rate of warming (c) for the period 2000-2100 and CS ranging from 2 to 10°C in the "interdependent" simulations (see text). Emissions correspond to SRES A1B (dashed lines) or an emission shutdown in 2020 (solid lines). Common climate policy targets are indicated by dotted grey lines. The ocean diffusivity is assumed to be 0.55 cm^2/s.

Figure 2. Warming after a shutdown of all emissions in 2020 (a) and following the A1B scenario in 2100 (b) depending on the CS ranging from 2 to 10°C and the AF calculated in either the "interdependent" approach or the "separate" approach by setting to the one for the simulation with a CS of 3°C (see text). The ocean diffusivity is assumed to be 0.55 cm^2/s. The error bars show the ranges of warming with the ocean diffusivity varied from 0.55 cm^2/s to 1.0 cm^2/s (middle bars) and 2.0 cm^2/s (lower bars).

“Correlation between climate sensitivity and aerosol forcing and its implication for the “climate trap””
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Figure 1

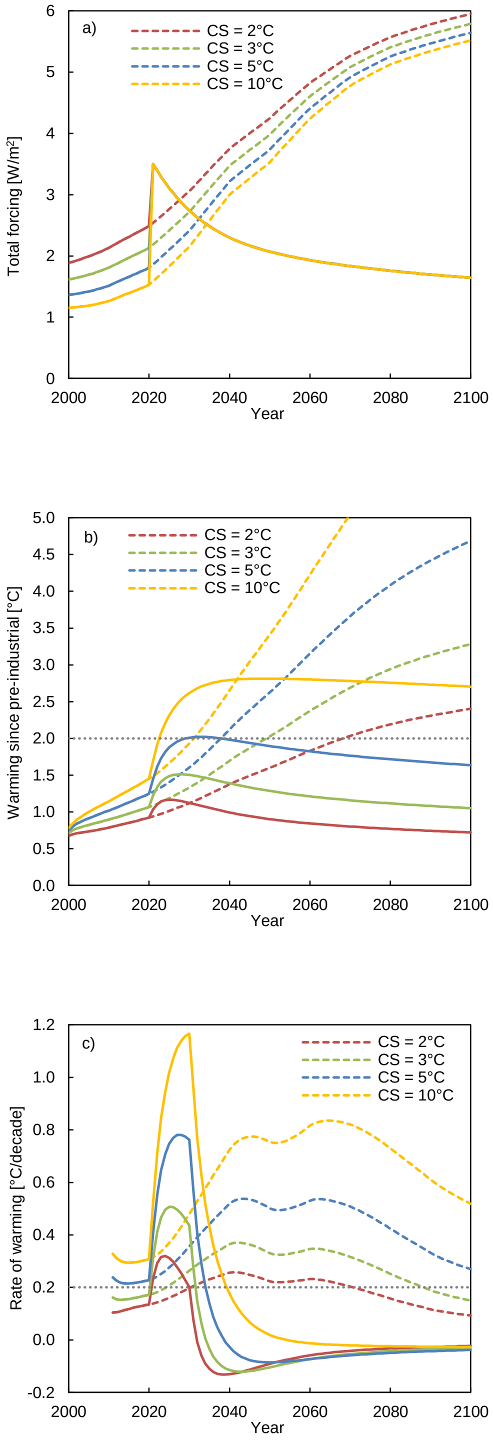

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Figure 2