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HOW MUCH WARMING ARE WE COMMITTED TO AND HOW MUCH CAN BE AVOIDED?

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Abstract

This paper examines different concepts of a 'warming commitment' which is often used in various ways to describe or imply that a certain level of warming is irrevocably committed to over time frames such as the next 50 to 100 years, or longer. We review and quantify four different concepts, namely (1) a 'constant emission warming commitment', (2) a 'present forcing warming commitment', (3) a 'zero emission (geophysical) warming commitment' and (4) a 'feasible scenario warming commitment'. While a 'feasible scenario warming commitment' is probably the most relevant one for policy making, it depends centrally on key assumptions as to the technical, economic and political feasibility of future greenhouse gas emission reductions. This issue is of direct policy relevance when one considers that the 2003 global mean temperatures were 0.8°C above the pre-industrial mean and the European Union has a stated goal of limiting warming to 2°C above the pre-industrial mean: What is the risk that we are committed to overshoot 2°C? Based on the conventional IPCC uncertainty range for climate sensitivity (1.5°C to 4.5°C) and more recent estimates, we found that a (1) constant emission scenario is virtually certain to overshoot 2°C with a central estimate of 2.0°C by 2100 (4.2°C by 2400). (2) While for the present radiative forcing levels it seems unlikely (risk between 0% and 30%, central estimate 1.1°C by 2100 and 1.2°C by 2400), the risk of overshooting is increasing rapidly if radiative forcing is stabilized much above today's levels (roughly 400ppm CO_2 equivalence) in the long-term. (3) From a geophysical point of view, if all human-induced emissions were ceased tomorrow, it seems 'exceptionally unlikely' that 2°C will be overshoot (central estimate: 0.7°C by 2100; 0.4°C by 2400). (4) Assuming future emissions according to the lower end of published mitigation scenarios provides (350ppm CO2eq to 450ppm CO2eq) the central temperature projections are 1.5°C to 2.1°C by 2100 (1.5°C to 2.0°C by 2400) with a risk to overshoot of 10% to 50% by 2100 and 1%-32% in equilibrium. Furthermore, we quantify the 'avoidable warming' to be 0.16-0.26°C for every 100GtC of avoided CO_2 emissions - based on a range of published mitigation scenarios.

Contents

1 Introduction

In this article we attempt to address - not finally answer – a key question: What warming can be avoided by climate policy and what cannot?

What warming and sea level rise we are committed to has a major bearing on issues such as the benefits of climate policy and to decisions relating to Article 2 of the UNFCCC which relates to the prevention of dangerous interference with the climate system. For example, as a first step to operationalize Article 2 of the UNFCCC the EU has set a global goal of limiting warming to 2°C above pre-industrial levels. With global mean temperatures in 2003 estimated to be 0.8°C above the pre-industrial mean (1861-1890) (Folland et al., 2001; Jones and Moberg, 2003)[i] the question arises of how much flexibility there is left in terms of greenhouse gas emissions in order to stay below the 2°C target.

If the climate and socio-economic systems lacked significant inertia the question of what warming is committed by past activities, and what is avoidable through policy action would not be of great concern. The fact that both systems have substantial inertia means that this deceptively simple question has quite complex scientific dimensions and far reaching policy implications. Lack of scientific certainty in relation to key climate system properties adds a further layer of complexity to the issue.

In this paper, we provide quantifications of four conceptually different 'warming commitments' resulting from (1) constant emissions, (2) constant greenhouse gas concentrations, (3) an abrupt cessation of emissions (defined here as the 'geophysical warming commitment'), and (4) from a range of feasible economic and technological emission scenarios. In addition to a systematic analysis of warming commitments, the question is addressed of how much warming is avoidable. Whilst it has been shown that there is little difference between the individual reference scenarios in the first several decades of this century (Stott and Kettleborough, 2002; Knutti et al., 2003), there has been little systematic examination of the differences between mitigation and non mitigation scenarios. Here we make a first examination of this issue on different decadal time frames across a range of mitigation and non-mitigation scenarios.

We start out by providing an overview of different concepts of a warming commitment and their respective limitations. Furthermore, a brief definition of the term "avoidable warming" is given (section 2). For most of our analysis, we rely on a simple upwelling-diffusion energy balance climate model. Special attention is paid to dealing with the uncertainty in the climate sensitivity (section 3). In the results section, we present the estimated 'warming commitments'. Whilst the focus is on global mean temperature change we also provide examples in relation to sea level rise. In addition, we estimate the potential for avoidable warming, and attempt to generalise the results in terms of avoided cumulative emission over decadal timeframes (section 4). In the penultimate section we discuss the results in terms of scientific uncertainties and their implications for long-term climate targets (section 5). Section 6 concludes.

2 Definitions: Different warming commitment concepts

The idea of a warming commitment is often used in climate policy and scientific discussions to convey the magnitude and time scales of inertia in the climate system with respect to human induced increases in greenhouse gas concentrations. At least two concepts of a warming commitment can be identified in the literature. Firstly, a scenario with constant emissions from some reference point, usually the present (IPCC, 2001a, p. 90). Secondly, a warming commitment estimate is sometimes derived from a constant radiative forcing scenario, usually also from present levels (see e.g. Wetherald et al., 2001). The latter concept is often used to illustrate a more general property of the climate systems caused by its inertia: the substantial time lag between the forcing and the full realization of the global mean temperature change resulting from that forcing.

In addition to these concepts we also developed two others. The first we term the 'geophysical warming commitment', which is the warming commitment resulting from a complete cessation of anthropogenic emissions. This captures the change in temperatures that result solely from geophysical and chemical processes without consideration of inertia in human, social and economic systems. The second concept we term the 'feasible scenario' commitment, which is an attempt to describe the interaction between the inertia of the climate system and socio-economic systems, as will be discussed below. Figure 1 shows schematically the relationship between these four concepts.

2.1 Constant emissions commitment

This is defined as the warming that would result at some determined time if present emissions continued indefinitely. Whilst sometimes used to illustrate a warming commitment, a main inconsistency is that humanity is not committed to keeping emissions at presently high levels. Whilst emissions are likely to rise in the near future there is every likelihood that at some point emissions would decline below present levels. In other words, constant emission scenarios do not indicate a warming commitment – unless today's emissions levels were considered as a lower bound for the coming decades and centuries.

2.2 Present forcing commitment

This is defined here as the warming (or sea level rise) that would result if the present level of forcing were maintained indefinitely (or over defined time periods). In other words, the 'present forcing' warming commitment is considered to be the sum of the 'realized' and 'unrealized' warming that corresponds to present day greenhouse gas concentrations or radiative forcing levels.

The concept of a present forcing commitment is often used to convey a sense of inertia to policy makers. For example, the IPCC WGI TAR report states that "Since the climate system requires many years to come into equilibrium with a change in forcing, there remains a 'commitment' to further climate change even if the forcing itself ceases to change." (Cubasch et al., 2001).

In terms of assessing a warming commitment that results from the inertia in both the climate and socio-economic system, the 'present forcing' commitment concept suffers from two problems, one obvious and the second perhaps less so. First, the greenhouse gas emission reductions required within a year or so to abruptly stabilize radiative forcing are unrealistically large. At the same time, emission from cooling aerosols would have to be kept at present (high) levels[ii]. Secondly, in the longer term (22nd century and beyond) it is by no means clear that radiative forcing would not drop below present levels. As a consequence it is not obvious that estimates of a 'warming commitment' based on constant radiative forcing is a lower bound on warming commitments in general, although it is sometimes interpreted that way. A scenario that has low emissions in the 22nd century and beyond could produce warming levels that approach or drop below the levels implied in a constant radiative forcing scenario (see Figure 6 c).

2.3 Geophysical commitment

A warming commitment can be defined from a purely geophysical perspective, as the warming that would result from a complete cessation of anthropogenic emissions. Such a thought experiment has value in terms of showing the timescales of the climate system without implicit entanglements with socio-economic assumptions.

An abrupt cessation of anthropogenic emissions is not at all likely, absent a global catastrophe. Hence, a geophysical warming commitment is primarily of interest when compared to 'feasible scenario' commitments. In this way, one can distinguish between the geophysical and socio-economic inertia components of a long-term future warming commitment. Note that an abrupt cessation of SO_2 emissions will cause an initial sharp increase in forcing and temperature levels, thereby overshooting a 'feasible scenario' commitment in the short-term (see Figure 1).

2.4 Feasible scenario commitment

A 'feasible scenario' warming commitment can be defined based on emission scenarios that are considered to be plausible in the sense that they are viewed as technologically, economically and politically feasible. Deriving such a 'feasible scenario' warming commitment requires specific assumptions to be taken about what are feasible rates of future emission reductions, not just in the short term but also over many decades. Such commitment estimates could be used to define the outer bounds of climate policy, beyond which policy tools and technology that are judged to be feasible cannot reach. Put another way, energy-economic models could be used to define the region of climate change space (warming and sea level rise) still accessible to policy and technology choices.

The estimates of warming commitments with respect to feasible scenarios rely on published examples of scenarios that stabilize CO_2 at or below 450ppm by 2100 by reputable modeling groups. Specifically, we used the post SRES A1F1-450 MiniCam, A1B-450 AIM, B1-450 IMAGE scenarios, the A1T–450 MESSAGE, and its WBGU variant (Nakicenovic and Riahi, 2003) as 450ppm CO_2 stabilization scenarios[iii]. In addition, we use recent scenarios for a CO_2 stabilization at 400ppm that were created by one of the modelling groups (MESSAGE) involved in the SRES and post-SRES scenarios and carried out for the German Global Change Advisory Council (WBGU) (Graßl et al., 2003), namely the WBGU B1-400 MESSAGE and the WBGU B2-400 MESSAGE scenarios (Nakicenovic and Riahi, 2003). Finally, we explore the implications of biomass scenarios, which also incorporate variants of carbon capture and storage. These latter CO_2-only scenarios aim to stabilize CO_2 at 350ppm (Azar et al., submitted) and were here complemented by the WBGU B2-400 non-CO_2 and landuse CO_2 emissions.

'Feasible scenario' warming commitments are perhaps the most realistic of definitions in the sense that socio-economic inertia is taken into account. However, the presented illustrative 'feasible scenario' commitments do not provide a definitive answer to what is the lower bound of future warming for several reasons. Mitigation options for important sectors such as agriculture, transport and industry are often not fully, or sometimes not at all, captured in the models used to generate mitigation scenarios. This results in higher concentrations of greenhouse gases than might otherwise be the case. Furthermore, there is substantial uncertainty in regard to the costs of mitigation scenarios, which influence judgements as to their plausibility. Costs are highly dependent on the assumed reference (non mitigation) case and the level to which technological learning is included.

Thus, a final answer on what may be a technologically, politically and economically feasible lower bound for warming over the next century and longer cannot be obtained based on scenarios that are presently judged to be feasible. Nevertheless the feasible scenario commitment appears to offer one of the more robust means of estimating the lower bound on warming.

2.5 What is avoidable warming?

When assessing climate policy options, policy makers often want to know what the avoidable warming is when comparing different mitigation and reference scenarios in the future. Whereas a 'warming commitment' is defined with respect to some fixed base climate state (here we have used the pre-industrial mean temperature from 1861 to 1890), avoidable warming is defined with respect to an assumed future evolution of emissions and the climate system. Thus, we provide estimates of avoidable warming by computing warming differences of paired mitigation and non-mitigation scenarios of the same SRES scenario family (see section 4.6).

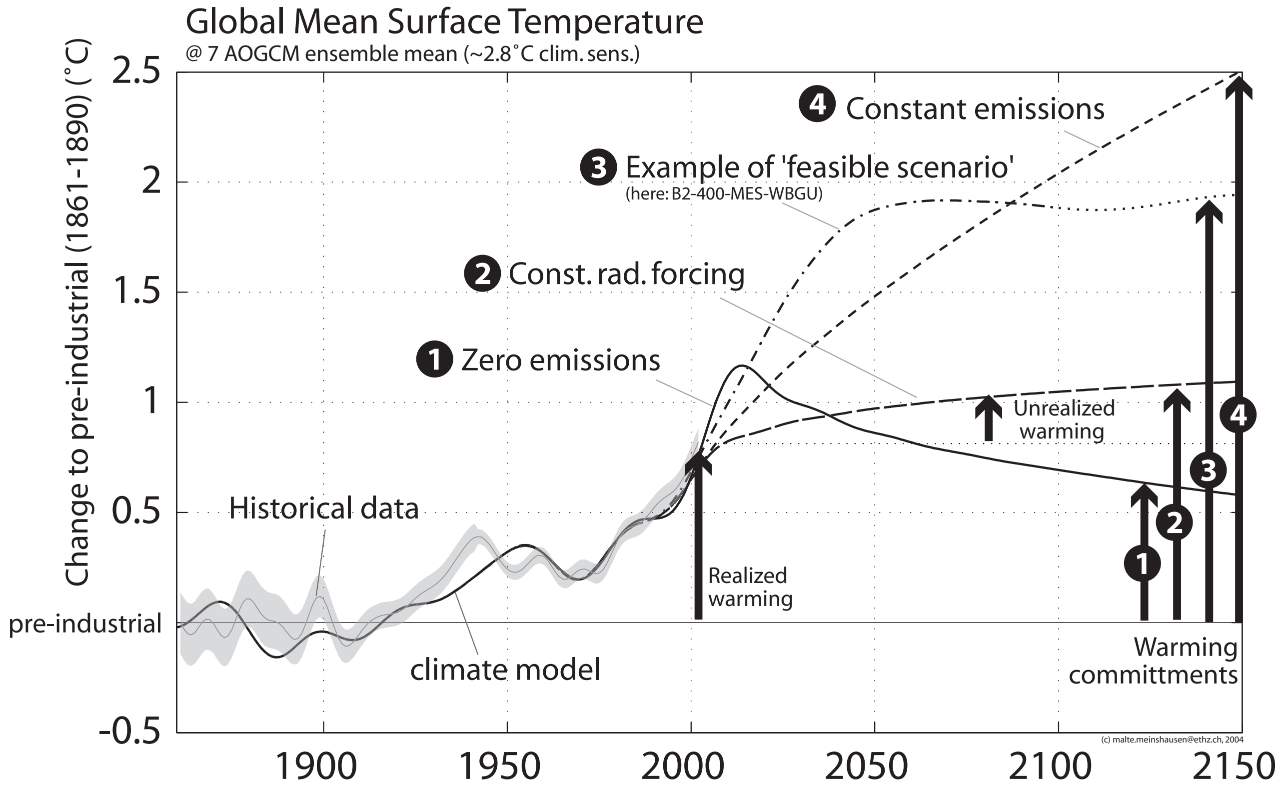

Figure 1 – Four different types of warming commitments. (1) The 'geophysical' warming commitment in case that emissions are abruptly reduced to zero after 2005 ('Zero Emissions'); Note that emissions initially rise due to ceased cooling by aerosols. (2) The 'present forcing' warming commitment corresponds to constant radiative forcing at present (2005) levels and comprises the 'realized' and 'unrealized' warming; (3) the 'feasible scenario' warming commitment is the temperature rise that corresponds to the lowest emission scenario judged feasible. Note that the mitigation scenario B2-400-MES-WBGU is shown for illustrative purposes only (dash-dotted line: original scenario up to 2100; dotted part: the extended scenario as described in text). Lastly, (4) the 'constant emissions' warming commitment that corresponds to highest warming levels in the long term. The historical temperature record and its uncertainty (grey shaded area) is taken from Folland et al. (2001).

3 Method

This section entails a brief description of the simple climate model MAGICC (3.1) employed in this work. In the non probabilistic components of this work we use a standard '7 AOGCM ensemble mean' procedure to average over model runs tuned to different AOGCMs (3.2). In addition, a probabilistic procedure allows us to give special attention to uncertainties in the climate's sensitivity based on a range of literature estimates (3.3). For additional equilibrium calculations standard formulas were applied (3.4). Finally we describe the assumptions made in regard to natural forcings (3.5).

3.1 Simple climate model

For the computation of global mean climate indicators, the simple climate model MAGICC 4.1 has been used[iv]. The description in the following paragraph is largely based on Wigley (2003). MAGICC is the primary simple climate model that has been used by the IPCC to produce projections of future sea level rise and global-mean temperatures. Information on earlier versions of MAGICC has been published in Wigley and Raper (1992) and Raper et al. (1996). The carbon cycle model is the model of Wigley (1993), with further details given in Wigley (2000) and Wigley and Raper (2001). Modifications to MAGICC made for its use in the IPCC TAR (IPCC, 2001b) are described in Wigley and Raper (2001; 2002) and Wigley et al. (2002). Additional details are given in the IPCC TAR climate projections chapter 9 (Cubasch et al., 2001). Sea level rise components other than thermal expansion are described in the IPCC TAR sea level chapter 11 (Church et al., 2001) with an exception in relation to the contribution of glaciers and small ice caps as described in Wigley (2003). Gas cycle models other than the carbon cycle model are described in the IPCC TAR atmospheric chemistry chapter 4 (Ehhalt et al., 2001) and in Wigley et al. (2002). The representation of temperature related carbon cycle feedbacks has been slightly improved in comparison to the MAGICC version used in the IPCC TAR, so that the magnitude of MAGICC's climate feedbacks are comparable to the carbon cycle feedbacks of the Bern-CC and the ISAM model (see Box 3.7 in Prentice et al., 2001)[v].

The gases that are modeled for each scenario are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), fluorinated gases (HFCs, PFCs, SF_6), and sulphur emissions (SOx) as well as carbon monoxide (CO), volatile organic compounds (VOC), and nitrogen oxide (NOx). If not otherwise stated, all indicated temperatures are annual and global mean surface temperature levels above pre-industrial levels (1861-1890). Sea level changes are indicated as changes in relation to 1990.

3.2 7 AOGCM ensemble mean

Ensemble mean outputs of this simple climate model are the basis for the non-probabilistic results presented in this study. The ensemble outputs are computed as means of seven model runs. In each run, 13 model parameters of MAGICC are adjusted to optimal tuning values for seven atmospheric-ocean global circulation models (AOGCMs) (see Raper et al. (2001). This '7 AOGCM ensemble mean' procedure is widely used in the IPCC Third Assessment Report and described in Appendix 9.1 (Cubasch et al., 2001). By using this '7 AOGCM ensemble mean' procedure, the implicit assumptions in regard to climate sensitivity is based on the seven AOGCMs. The mean climate sensitivity for those 7 AOGCMs models is 2.8°C for doubled CO_2

concentration levels (median is 2.6°C). Clearly, different climate projections would be obtained, if single model tunings or different climate sensitivities were used, reflecting the underlying uncertainty in the science.

3.3 Handling uncertainties: climate sensitivity

In addition to these '7 AOGCM ensemble mean' runs, another approach had to be chosen to deal with the main climate system uncertainty, the climate sensitivity. The climate sensitivity is simultaneously one of the most fundamental and uncertain properties of the climate system in relation to policy. Following the convention in the literature it is defined as the equilibrium increase in global mean surface temperature following a doubling of pre-industrial CO_2 levels (2 x 278=556ppm). Thus, estimates of the climate sensitivity approximately reflect the equilibrium warming that can be expected under a 550 CO_2 equivalent stabilization scenario.

There is no single universally agreed estimate of climate sensitivity or even of a probability density functions for it. We have attempted to deal with this uncertainty by making probabilistic calculations for temperature projected for different probability density functions of climate sensitivity. Whilst varying the climate sensitivity parameter we have maintained the default set of climate parameters for MAGICC consistent with the IPCC Third Assessment Report findings (Wigley, 2003).

Clearly, this procedure does not take into account interdependencies between climate sensitivity and other climate parameters, such as ocean heat diffusion. Ideally, the simple climate model should be run for parameter sets from a joint probability density distribution for the key uncertainties. In the absence of published joint probability estimates, we choose to focus only on climate sensitivity and neglect interdependencies as well as uncertainties in other key climate parameters. This should be kept in mind when reviewing the results.

Since its First Assessment Report in 1990, the IPCC has indicated that the climate sensitivity is most likely to lie in the range 1.5-4.5°C. Prior to the IPCC TAR the IPCC had given a best estimate of 2.5°C. However, in the TAR no reference was made to a best estimate and instead to an average model range. Hence there is no real quantitative guidance at this stage arising from the IPCC assessments other than by the "likelihood" of the climate sensitivity lying in range 1.5°C to 4.5°C.

After the completion of the IPCC TAR, a number of estimates of the climate sensitivity have been published with probability density functions (PDFs), each with its own strengths and weaknesses (see e.g. IPCC, 2004). Eight of these estimates are used in the subsequent analysis and shown in Figure 2[vi]: Six are based on contemporary forcing history and the recent evolution of the climate system: (1) the combined PDF by Andronova and Schlesinger (2001) that takes into account both solar forcing and sulphate aerosols[vii]; (2-3) estimates by Forest et al. (2002a) with expert and uniform a priori distributions; (4) another observationally based estimate by Gregory et al. (2002); (5) the uniform prior estimate by Knutti et al. (2003); (6) a recent estimate based on a 53 ensemble of a large GCM, HadAM3 (Murphy et al., 2004). (7) The seventh is drawn from the conventional 1.5°C to 4.5°C IPCC uncertainty range. This range has been assumed by Wigley and Raper (2001) as being a log-normal 90% confidence range. (8) The last PDF estimate is based on recent work by Schneider von Deimling et al. at the Potsdam Institute of Climate Impact Research using estimated climate and radiative changes at the Last Glacial Maximum (LGM) compared to the recent Holocene: Their best estimate of sensitivity is 2.1ºC to 3.6ºC, with a range of 1.5ºC to 4.7ºC (see e.g. report by Kerr (2004)[viii]. In order to illustrate implications of a narrow PDF, we choose the 90% confidence range (2.1°C to 3.6°C) for a 'best estimate' of palaeoclimatic tropical sea surface temperatures. Based on this range, we constructed a lognormal PDF as Wigley and Raper did for the conventional IPCC range. For some of our results, we chose to focus on the latter PDFs (5) to (8). These latter four studies span the range of available climate sensitivity PDF estimates in terms of their shape and methods by which they have been derived (see Figure 2).

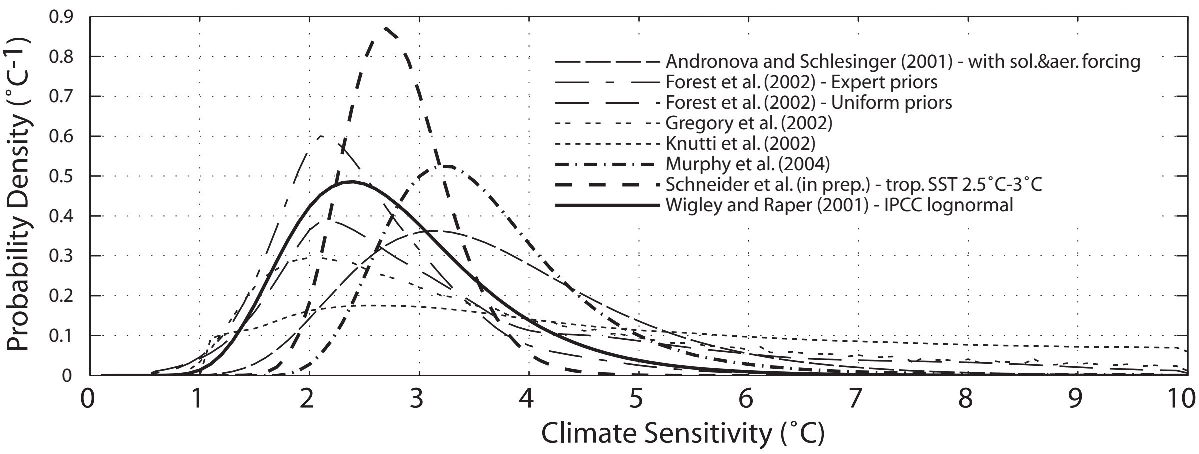

Figure 2 - Different estimates of the probability density functions for climate sensitivity.

3.4 Time Horizon, equilibrium considerations and CO_2 equivalence

The time horizon used to explicitly evaluate warming commitments based on defined scenarios here is to the year 2400. This is arbitrary given that the climate system will continue to respond well beyond this time. As has been shown the warming following greenhouse gas concentration stabilization will continue for a few thousand years and only slowly approach equilibrium (Watterson, 2003).

As in the MAGICC climate model, the following formula is used for the presented equilibrium calculations (see as well Ramaswamy et al., 2001, Table 6.2, page 358). The conversion between CO_2 (equivalence) concentrations and radiative forcing (ΔQ) follows the logarithmic equation:

$$\Delta Q = \alpha \ln\left(C / C_0 \right) \quad (1)$$

where α is 5.35 and C_0 the unperturbed pre-industrial CO_2 concentration level (278ppm), based on Myhre et al. (1998). The equilibrium temperature is then assumed to scale linearly with radiative forcing:

$$\Delta T = \Delta Q \frac{\Delta T_{2xCO2}}{\alpha \ln(2)} \quad (2)$$

where ΔT_{2xCO2} is the climate sensitivity and α*ln(2) is the radiative forcing for twice the pre-industrial CO_2 levels.

CO_2 equivalent concentrations are here derived from the net forcing of all anthropogenic radiative forcing agents. Thus, CO_2 equivalence comprises both greenhouse gases and aerosols but not natural forcings.

3.5 Natural forcings

If not otherwise stated, historic solar and volcanic forcings have been assumed, according to Lean et al. (1995) and Sato et al. (1993), respectively, as presented in the IPCC TAR (see Figure 6-8 in Ramaswamy et al., 2001). Recent studies suggested that an up-scaling of solar forcing might lead to a better agreement of historic temperature records (e.g. Hill et al., 2001; North and Wu, 2001; Stott et al., 2003). In accordance with the best fit results by Stott et al. (2003, table 2), a solar forcing scaling factor of 2.64 has been assumed for this study. Accordingly, volcanic forcings from Sato et al. (1993) have been scaled down by a factor 0.39 (Stott et al., 2003, table 2). Future solar and volcanic forcings have been assumed in accordance with the mean forcings over the past 22 and 100 years respectively, i.e. +0.16 W/m^2 for solar and -0.35 W/m^2 for volcanic forcing and scaled as described above[ix].

It should be noted that mechanisms for the amplification of solar forcing are not yet well established (Ramaswamy et al., 2001, section 6.11.2; Stott et al., 2003). As well, the evidence for the conventionally assumed long-term solar irradiance changes has recently been challenged (Foukal et al., 2004).

An exception has been made for the calculations on the risk of overshooting certain temperature levels in equilibrium (section 4.5). There, equilibrium temperatures have been directly derived from anthropogenic radiative forcings. Thus, natural forcings have implicitly been assumed constant at pre-industrial levels. This approach allows to separate risks that solely accrue from human interference and those that accrue from changes in natural forcings. Assuming no change of natural forcings since pre-industrial times will lower the presented temperature increase by 0.35°C in equilibrium for the 7 AOGCM ensemble mean runs (see Table I, Table II and Table III). Thus, it should be noted that the presented overshooting risks are lower than if the above standard assumptions on natural forcings were applied.

4 Results: The warming commitments and avoidable warming

Below we first outline the results of the analysis for the warming commitments based on the four concepts outlined at the beginning of the paper: (4.1) constant emissions, (4.2) constant radiative forcing at present day levels, the 'present forcing' warming commitment, (4.3) the 'geophysical' warming commitment, defined as the effects of a complete and abrupt cessation of all human-induced emissions, and (4.4) the 'feasible scenario' warming commitment. We then provide a compilation of results by deriving the probability that we are already 'committed' to overshoot certain warming levels (4.5). Finally, we present estimates of the scale of avoidable warming by analysing paired mitigation and non-mitigation scenarios (4.6).

4.1 Constant emissions

If greenhouse gas and aerosol emissions were held constant at present day (2005) levels, CO_2 (equivalent) concentrations would rise up to 531 (527)ppm by 2100 and 929 (899)ppm by 2400. Temperature would increase monotonically up to 4.2°C in 2400 (2.0°C in 2100) – according to the '7AOGCM ensemble mean'. Assuming lower (1.5°C) and higher (4.5°C) climate sensitivities, the temperature range in 2400 spans from 2.5°C to 6.1°C, respectively (2100: 1.4°C to 2.7°C)[x]. The 90% confidence ranges for global mean temperatures based on climate sensitivity estimates by Murphy et al. (2004) is 1.9°C to 3.0°C in 2100 and 3.7°C to 7.0°C by 2400. See Table I for further estimates for different climate sensitivity PDFs.

The projected sea level rise is 28cm (7 AOGCM ensemble mean) with a 22 to 40 cm range when assuming the conventional IPCC climate sensitivity uncertainty. By 2400, sea level will have risen 87 cm with a range from 65 cm to 121 cm (see Table I and Figure 3). Note that the overall uncertainty in sea level rise is significantly bigger than shown above, since other important parameters for sea level rise projections - apart from climate sensitivity - are here assumed according to default IPCC TAR values.

Table I - 'Constant emission' warming commitment: temperature and sea level implications in the case where emissions are held constant at today's (2005) levels. Results are given for the '7 AOGCM ensemble mean' as well as the probabilistic calculations based on different estimates of climate sensitivity PDFs by Wigley & Raper (2001), Murphy et al. (2004), Schneider von Deimling (see Kerr, 2004), and Knutti et al. (2003). In addition, equilibrium temperatures for 2400 forcing levels are given with applying the standard natural forcing assumptions (EQUI w NF) and without assuming any natural forcing changes from pre-industrial levels (EQUI w/o NF).

	Temperature above pre-industrial (°C above pre-industrial)								Sea level above 1990 (cm above 1990)					
Climate Sensitivity	2000	2005	2050	2100	2200	2400	EQUI w NF	EQUI w/o NF	2000	2005	2050	2100	2200	2400
7 AOGCM ensemble mean														
~2.8	0.7	0.8	1.5	2.0	2.9	4.2	5.2	4.9	2	3	15	28	53	87
Wigley														
5%: 1.50	0.5	0.6	1.0	1.4	1.8	2.5	2.7	2.6	1	2	12	22	42	65
50%: 2.60	0.6	0.8	1.4	2.0	2.8	4.0	4.8	4.5	2	3	16	30	55	87
95%: 4.50	0.7	0.9	1.9	2.7	4.1	6.1	8.5	7.9	2	4	20	40	70	121
Murphy														
5%: 2.40	0.6	0.7	1.4	1.9	2.6	3.7	4.4	4.1	2	3	15	29	53	83
50%: 3.42	0.7	0.8	1.7	2.3	3.4	5.0	6.4	6.0	2	3	18	35	62	102
95%: 5.37	0.8	0.9	2.0	3.0	4.6	7.0	10.2	9.5	2	4	22	43	76	135
Schneider														
5%: 2.10	0.6	0.7	1.3	1.7	2.4	3.3	3.9	3.6	2	3	14	27	49	77
50%: 2.72	0.7	0.8	1.5	2.0	2.9	4.1	5.0	4.7	2	3	16	31	56	89
95%: 3.60	0.7	0.8	1.7	2.4	3.5	5.2	6.7	6.3	2	3	18	36	63	105
Knutti														
5%: 1.47	0.5	0.6	1.0	1.3	1.8	2.5	2.7	2.5	1	2	12	22	41	64
50%: 4.33	0.7	0.9	1.9	2.7	4.0	6.0	8.1	7.6	2	4	20	39	69	118
95%: 9.28	0.9	1.1	2.5	3.9	6.2	>8	18.1	17.0	3	5	26	52	95	185

4.2 The 'present forcing' warming commitment

One of the scenarios often used to convey a sense of inertia and of committed warming to policy makers is that of holding radiative forcing constant from a certain point in time.

The Hadley Centre, for example, recently estimated the additional warming that would follow from stabilization of greenhouse gas concentrations at present levels (see thick dotted line in panel c of Figure 3). The total warming above pre-industrial by 2100 was estimated by about 1.1°C with an ultimate warming of 1.6°C over many centuries (Hadley Centre, 2002, p. 3; 2003, p. 12)[xi]. Other models yield similar estimates when holding radiative forcing constant. Using a climate model with higher sensitivity (3.7°C) than in the Hadley Centre analysis, the results of Wetherald et al. (2001)[xii] indicate a total warming at equilibrium of around 2.1°C above 1861-1890 would occur with forcing held constant at year 2000 levels [xiii].

In this study, results suggests an increase of global mean surface temperatures by about 0.5°C up to 2400 over 2000 levels (1.2°C above pre-industrial), if radiative forcing were held fixed at present levels (estimated to be 368ppm CO_2 equivalent from 2005) ('7 AOGCM ensemble mean'). In equilibrium, temperatures are estimated to rise up to 1.5°C above pre-industrial values if assumptions on current natural forcing continue to apply. If no change of natural forcing since pre-industrial times were assumed, the equilibrium warming would be about 0.35°C lower, namely 1.2°C.

Running the simple climate model with default IPCC TAR parameter settings, but the IPCC bounds of climate sensitivity (1.5°C and 4.5°C), the 2400 total warming lies between 0.8°C and 1.7°C. The central estimate for sea-level rise is 46cm above 1990 levels (41 to 57 cm range) (cp. Figure 3 and Table II). At equilibrium the warming range would be 0.8 to 2.4°C (cf. Table II).

It should be kept in mind that the present forcing is dampened greatly by the cooling effect of aerosols that counteracts the warming effect of greenhouse gases, although the magnitude is uncertain. Thus, the present forcing warming commitment might be up to 1.9 (2.1) °C by 2100 (2400) for the '7AOGCM ensemble mean', when assuming that SO_2 aerosol emissions were ceased, but greenhouse gas concentrations remain at the current level (452ppm CO_2 equivalence)[xiv].

Table II - 'Present forcing' warming commitment: temperature and sea level implications in case that radiative forcing is held constant at today's (2005) levels (368ppm CO_2 equivalence). Otherwise as Table I.

	Temperature above pre-industrial (°C above pre-industrial)								Sea level above 1990 (cm above 1990)					
Climate Sensitivity	2000	2005	2050	2100	2200	2400	EQUI w NF	EQUI w/o NF	2000	2005	2050	2100	2200	2400
7 AOGCM ensemble mean														
~2.8	0.7	0.8	1.0	1.1	1.1	1.2	1.5	1.2	2	3	11	19	31	46
Wigley														
5%: 1.50	0.5	0.6	0.7	0.7	0.8	0.8	0.8	0.6	1	2	9	15	26	41
50%: 2.60	0.6	0.7	0.9	1.0	1.1	1.1	1.4	1.1	2	3	12	20	33	48
95%: 4.50	0.7	0.9	1.2	1.4	1.5	1.7	2.4	1.9	2	4	16	26	42	57
Murphy														
5%: 2.40	0.6	0.7	0.9	1.0	1.0	1.1	1.3	1.0	2	3	12	19	32	47
50%: 3.42	0.7	0.8	1.1	1.2	1.3	1.4	1.8	1.4	2	3	14	23	37	52
95%: 5.37	0.8	0.9	1.3	1.5	1.7	1.9	2.9	2.2	2	4	17	28	45	60
Schneider														
5%: 2.10	0.6	0.7	0.8	0.9	0.9	1.0	1.1	0.9	2	3	11	18	30	45
50%: 2.72	0.7	0.8	1.0	1.0	1.1	1.2	1.5	1.1	2	3	12	21	34	48
95%: 3.60	0.7	0.8	1.1	1.2	1.3	1.4	1.9	1.5	2	3	14	24	38	53
Knutti														
5%: 1.47	0.5	0.6	0.7	0.7	0.8	0.8	0.8	0.6	1	2	9	15	25	40
50%: 4.33	0.7	0.9	1.2	1.3	1.5	1.7	2.3	1.8	2	4	15	26	41	56
95%: 9.28	0.9	1.1	1.7	2.0	2.3	2.8	5.0	3.9	3	5	20	34	53	73

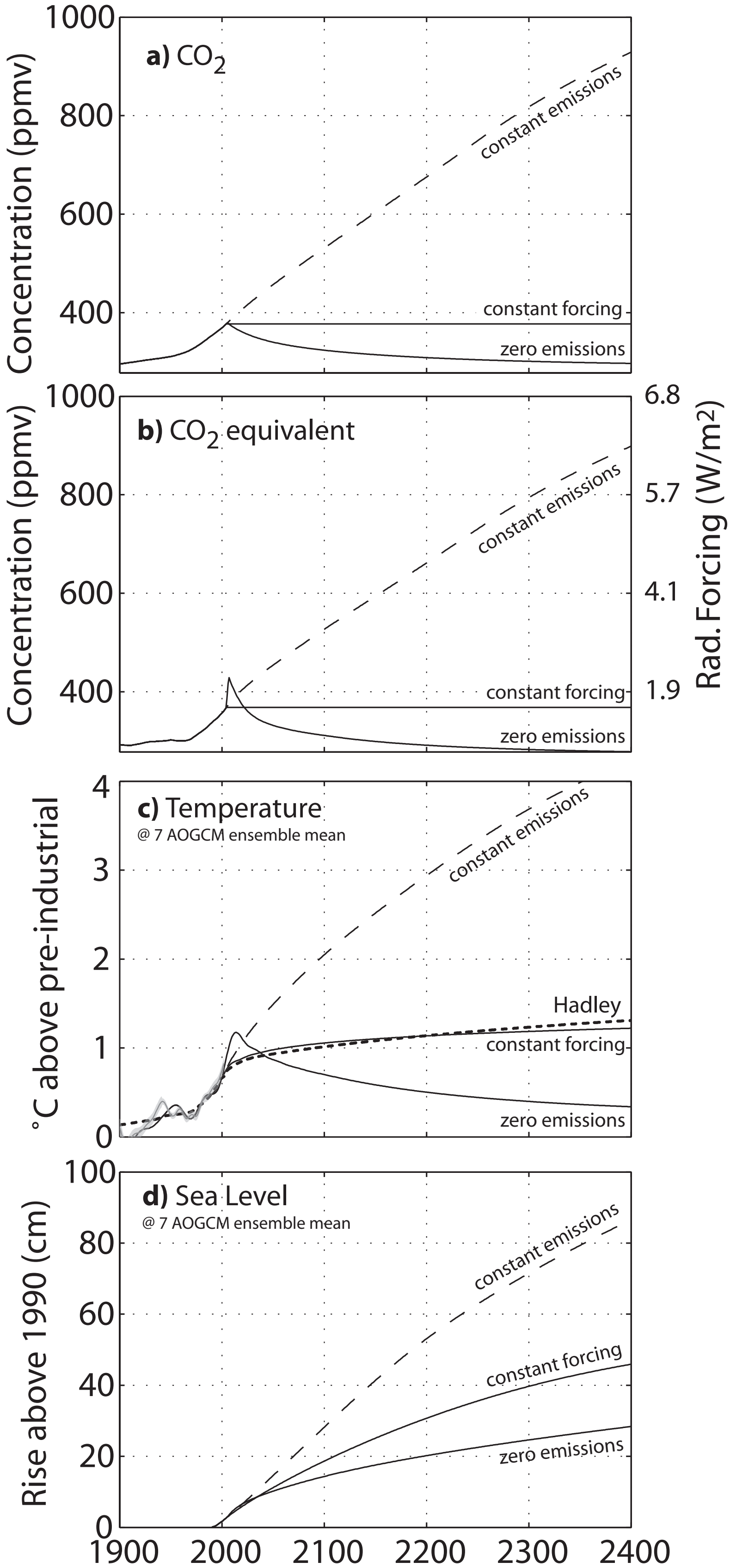

Figure 3 - Effects of abrupt cessation of emissions, constant radiative forcing, and constant emissions from 2005 onwards (a) CO_2 concentrations, (b) CO_2 equivalent concentrations and radiative forcing, (c) global mean surface temperature and (d) sea level rise. Shown are results of the '7 AOGCMs ensemble mean' runs with an approximate climate sensitivity of 2.8°C. The Hadley centre's estimate of the warming commitment related to a constant radiative forcing (dotted line in panel c) (Hadley Centre, 2002) is approximately equivalent to the '7 AOGCM ensemble mean' one derived here.

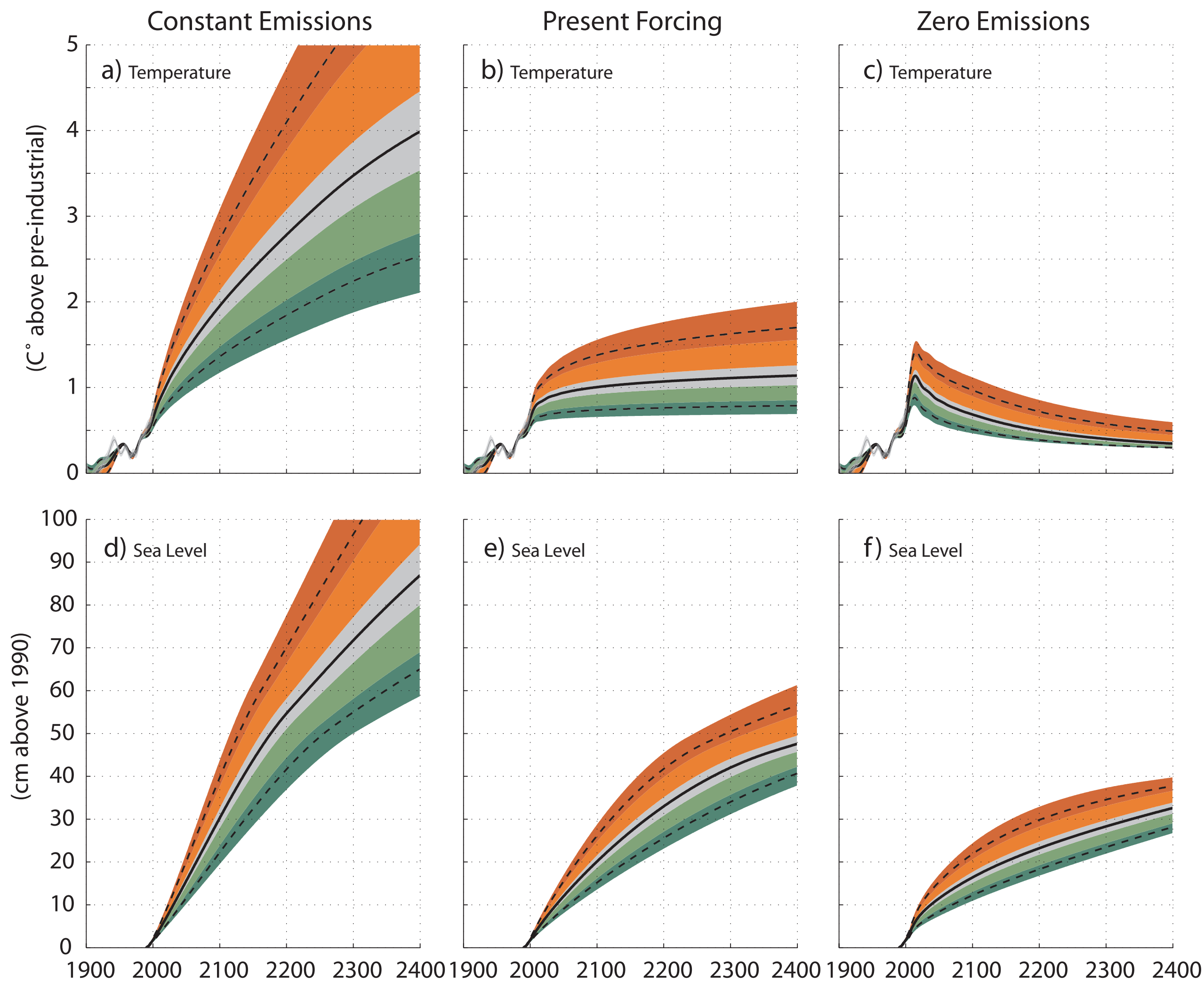

Figure 4 - Global mean temperature increase and sea level rise in case that emissions are held constant at 2005 levels (left a,d), that radiative forcing is held constant (middle b,e) or that emissions are abruptly reduced to zero (right c,f). Likelihood ranges are given for the lognormal fit to the conventional 1.5-4.5°C IPCC range (Wigley and Raper, 2001): the 90% confidence range (dashed lines), the median projection (solid line), as well as the 1%, 10%, 33%, 66%, 90% and 99% percentiles (borders of shaded areas). Note that only a small part of the full uncertainty in sea level rise is shown, namely the part that stems from uncertainty in climate sensitivity.

4.3 The 'geophysical' warming commitment and its increase over time

A complete and abrupt cessation of human emissions would soon reverse the increase in radiative forcing and result in a halt to global mean temperature increase and a significant slow down in sea level rise. However, in the beginning, the cessation of sulphur emissions causes a short, but pronounced, increase in net radiative forcing and temperatures (Wigley, 1991). Within a decade temperatures would be begin to fall, though (Figure 3.c). Still, over the 21st century, it seems likely that temperature levels at least as high as year 2000 levels would prevail, even if all human-induced emissions were halted today. However, beyond 2100, there is no geophysical commitment to a further increase in warming, but there is a floor to how fast temperatures can drop[xv]. The indicated lower bound of approximately 0.3°C to 0.4°C results largely from the assumed increase in solar forcing since pre-industrial times (see section 3.5). CO_2 concentrations would fall slowly and approach levels that were found at the beginning of the 20th century towards the end of the 22nd century, namely 300ppm (see Figure 3.a). Note that CO_2 equivalent concentrations might fall below levels of CO_2 concentrations, because pre-industrial emissions levels of N_2O and methane were not zero due to pre-industrial sources from agricultural activities (cf. Figure 3.b). The slow take up of the airborne fraction of anthropogenic carbon emissions by the oceans determines the rates of temperature reduction in the 22nd century and beyond and also ultimately determines the rise in sea level.

In contrast to temperatures and CO_2 concentrations, the sea level is likely to rise for many centuries, even if emissions were halted today. This is due to the slow thermal expansion of the ocean and continued melting of ice sheets and glaciers, which add to the total mass of the ocean (cp. Raper et al., 1996). The geophysical sea level rise commitment defines a lower bound of about 30 cm – based on the simple climate model used here and standard IPCC TAR parameters (Figure 3.d) [xvi].

In order to see how the geophysical warming commitment increases with time, we have shown the effects of emissions being switched off at six ten-year intervals from 2001 to 2051 for the SRES A1B scenario on both sea level rise and temperature. This may help place lower bounds on the costs of delaying policy action (see section 5.2). The additional 'warming commitment' by 2100 increases by about 0.2-0.3°C for each 10-year delay and over the period to 2400 by 0.1-0.2°C. The additional sea level rise by 2100 increases by about 2-4 cm for each 10-year delay for times around 2100 and beyond (see Table IV and Figure 5).

Table III - 'Geophysical' warming commitment: temperature and sea level implications in case that all emissions are ceased from 2005. Otherwise as Table I.

	Temperature above pre-industrial (°C above pre-industrial)								Sea level above 1990 (cm above 1990)					
Climate Sensitivity	2000	2005	2050	2100	2200	2400	EQUI w NF	EQUI w/o NF	2000	2005	2050	2100	2200	2400
7 AOGCM ensemble mean														
~2.8	0.7	0.8	0.9	0.7	0.6	0.4	0.4	0.1	2	3	10	15	21	29
Wigley														
5%: 1.50	0.5	0.7	0.6	0.5	0.4	0.3	0.2	0.0	1	2	8	12	18	28
50%: 2.60	0.6	0.8	0.8	0.7	0.5	0.3	0.4	0.1	2	3	12	16	23	33
95%: 4.50	0.7	1.0	1.2	1.0	0.7	0.5	0.7	0.1	2	4	15	22	30	38
Murphy														
5%: 2.40	0.6	0.8	0.8	0.7	0.5	0.3	0.3	0.1	2	3	11	16	22	32
50%: 3.42	0.7	0.9	1.0	0.8	0.6	0.4	0.5	0.1	2	3	13	19	26	35
95%: 5.37	0.8	1.0	1.3	1.1	0.8	0.6	0.8	0.2	2	4	17	24	32	39
Schneider														
5%: 2.10	0.6	0.8	0.8	0.6	0.4	0.3	0.3	0.0	2	3	10	15	21	31
50%: 2.72	0.7	0.8	0.9	0.7	0.5	0.4	0.4	0.1	2	3	12	17	24	33
95%: 3.60	0.7	0.9	1.0	0.8	0.6	0.4	0.5	0.1	2	3	14	20	27	36
Knutti														
5%: 1.47	0.5	0.7	0.6	0.5	0.4	0.3	0.2	0.0	1	2	8	12	18	28
50%: 4.33	0.7	1.0	1.1	0.9	0.7	0.5	0.6	0.1	2	4	15	21	29	37
95%: 9.28	0.9	1.2	1.6	1.5	1.2	0.9	1.5	0.4	3	5	21	30	40	46

Table IV – The geophysical warming commitment over time (columns) is depending on the year, when emissions are reduced to zero (rows). Before being ceased, emissions were assumed to follow the SRES A1B-AIM baseline scenario (cp. Figure 5). Results are shown for the '7 AOGCM ensemble mean' and equilibrium values with and without natural forcing ('EQUI w NF' and 'EQUI w/o NF', respectively).

	Temperature above pre-industrial (°C above pre-industrial)								Sea level above 1990 (cm above 1990)					
Ceasing emissions	2000	2005	2050	2100	2200	2400	EQUI w NF	EQUI w/o NF	2000	2005	2050	2100	2200	2400
2001	0.7	1.1	0.8	0.7	0.5	0.3	0.4	0.0	2	3	10	14	20	28
2011	0.7	0.7	1.0	0.8	0.6	0.4	0.5	0.1	2	3	12	16	23	31
2021	0.7	0.7	1.3	1.0	0.8	0.6	0.6	0.3	2	3	14	19	26	34
2031	0.7	0.7	1.7	1.3	1.0	0.7	0.8	0.4	2	3	16	22	30	37
2041	0.7	0.7	2.1	1.6	1.2	0.9	0.9	0.6	2	3	17	26	34	40
2051	0.7	0.7	2.2	1.9	1.4	1.1	1.1	0.8	2	3	18	29	38	43

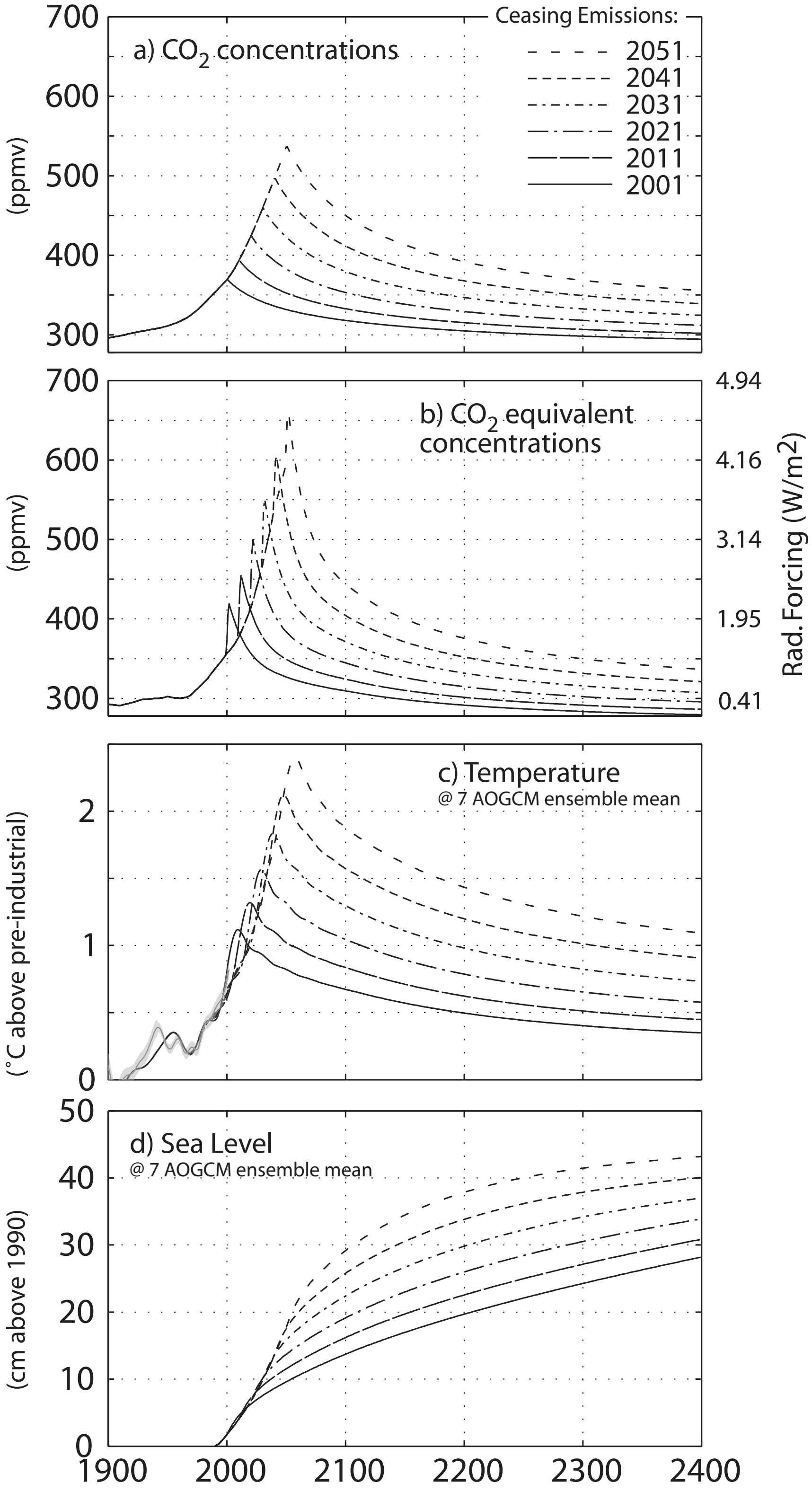

Figure 5 -Effects of 10 year lags in reducing emissions to zero on (a) CO_2 concentrations, (b) CO_2 equivalent concentrations and radiative forcing, (c) global mean temperature, and (d) sea level rise. Emissions are reduced to zero in 2001, 2011,..,2051 after following the SRES A1B-AIM scenario.

4.4 The 'feasible scenario' warming commitment

We now turn to an examination of what the warming commitment might be for a range of feasible emissions scenarios. We use explicit scenarios from the literature that produce a range of different radiative forcing pathways (see section 2.4). If not otherwise indicated, all results below refer to the 7 AOGCM ensemble mean results (see section 3.2). Furthermore, we examine the equilibrium warming when forcing is stabilized at a range of CO_2 equivalent levels (see method's section 3.4).

For the period up to 2100, the 450ppm CO_2 scenarios result in a warming in the range of 2.2-2.4°C above pre-industrial levels ('7 AOGCM ensemble mean'). An exception is the A1FI-450 MiniCam scenario that results in higher warming (3.0°C) due to very high unabated N_2O emissions. For the two 400ppm scenarios the range is 1.9-2.1°C in 2100. The 350ppm CO_2 stabilization scenarios of Azar et al. (submitted) yield a warming of about 1.5-1.7°C by 2100[xvii]. In contrast, temperatures in 2100 will increase to levels that are between 2.5°C to 4.8°C above pre-industrial ones, if emissions were to follow one of the non-mitigation scenarios analysed here (see Figure 6).

The projected spread in sea-level rise over all scenarios is limited until 2050, specifically from 15.1 to 18.3 cm ('7 AOGCM ensemble means'). In 2100, the 450ppm CO_2 stabilization scenarios correspond to an estimated sea-level rise of 30 to 35 cm above 1990. Sea-level will be slightly lower, if emissions were to follow the 400ppm CO_2 stabilization scenarios (28 to 30 cm) or the 350ppm CO_2 scenarios (25 to 28 cm). In the non-mitigation scenarios, sea-level is projected to increase by 33 to 50 cm above 1990 levels.

As mentioned before, the 350ppm and 400ppm CO_2 stabilization scenarios produce total warming estimates between 1.5°C and 2.1°C by 2100 under the '7 AOGCM ensemble mean' procedure. In other words, if such scenarios were considered to represent the outer limit of where climate policies can reach, we would be committed to an additional warming of 0.7 to 1.3°C above the warming of 0.8°C in 2003 (Folland et al., 2001; Jones and Moberg, 2003).

The period beyond 2100 is critical to warming commitment assessments. However, published mitigation scenarios are generally limited to 2100. Therefore, we have extended these scenarios so that they stabilize CO_2 concentrations at the indicated levels. For example, the WBGU B2-400 MESSAGE scenario is extended so that CO_2 concentrations stabilize at 400ppm. The emissions of other greenhouse gases and aerosols beyond 2100 are assumed to correlate with the extended fossil CO_2 emissions in a specific way, namely by making use of the 2100 emission characteristics of 54 SRES and post-SRES scenarios via the 'Equal Quantile Walk' method (Meinshausen et al., submitted)[xviii]. A special case is the AZAR-350-BECS scenario, where the fossil CO_2 emissions are negative (-3.6 GtC/yr) in 2100 and assumed to smoothly return to zero by 2200. As a consequence, CO_2 concentrations will stabilize at about 310ppm and CO_2 equivalent concentrations at about 350ppm by 2150 (see Table V).

By 2400, temperatures would have risen to 1.5°C, 2.0°C and 2.4°C for the 350ppm, 400ppm and 450ppm CO_2 stabilization scenarios, respectively, according to the '7 AOGCM ensemble mean'. Temperatures for the AZAR-350-BECS scenario, which is assumed to stabilize at the lowest CO_2 level of 310ppm, would have returned to about 1.2°C by 2400. By 2400, sea level will have risen between 40 cm and 60 cm for the analysed mitigation scenarios (see Figure 6).

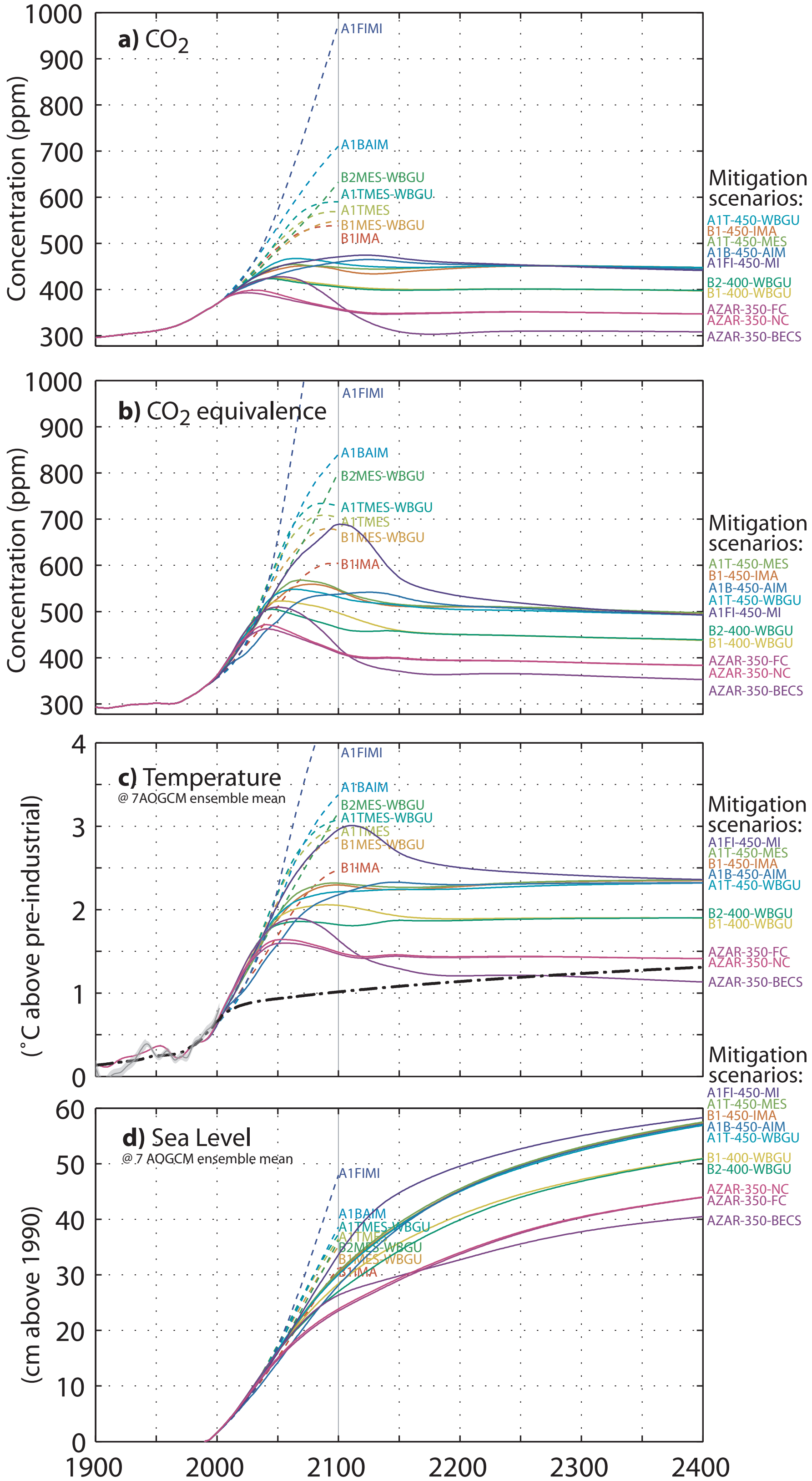

Figure 6 - The climatic effects of a range of SRES non-mitigation scenarios (dotted line) and 350-450ppm CO_2 stabilization scenarios (solid lines) on (a) CO_2 concentrations, (b) CO_2 equivalent concentration and radiative forcing, (c) global mean temperatures and (d) sea level up to 2100. For comparison, the Hadley estimate of the present warming commitment is plotted as in Figure 3.

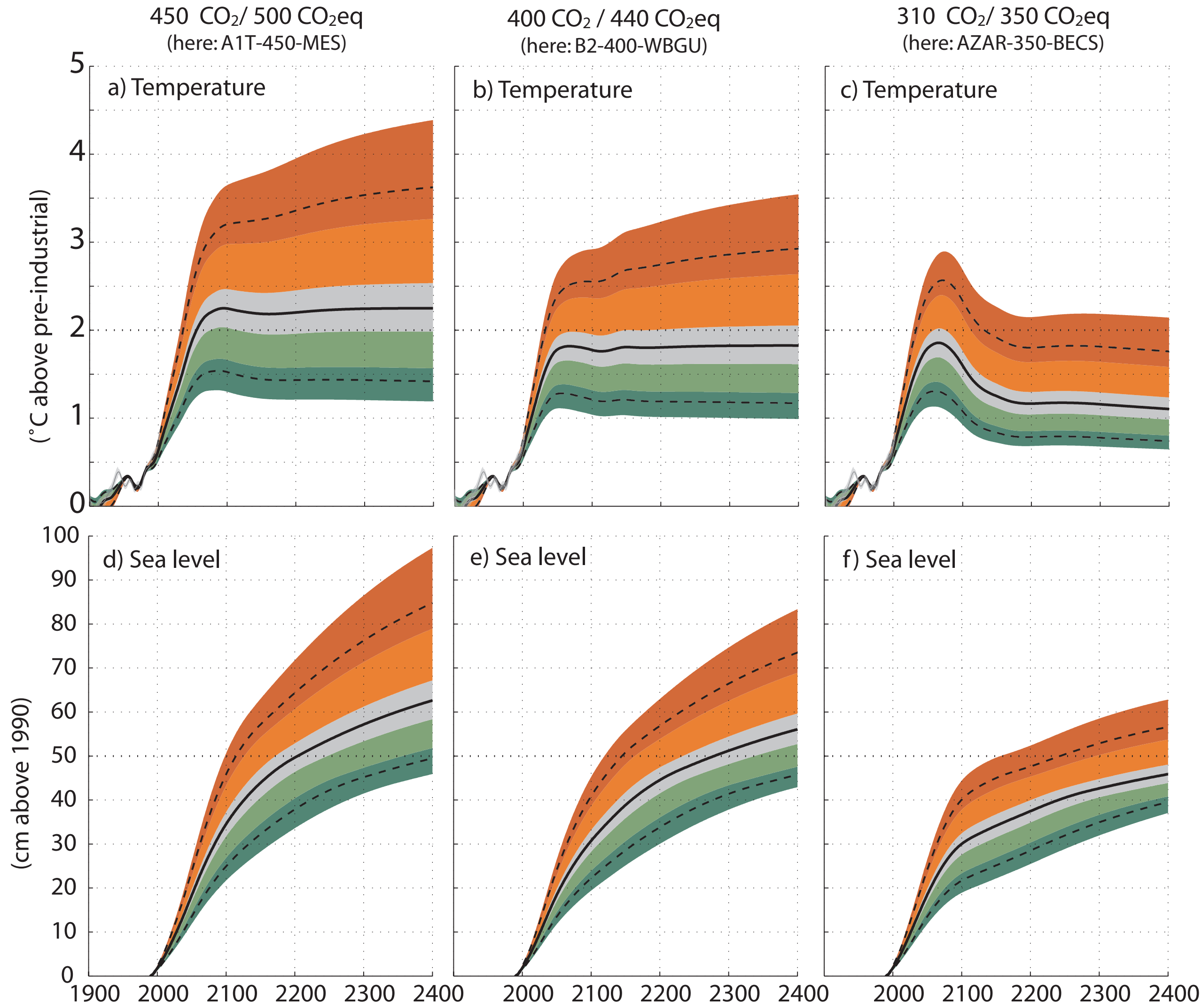

Figure 7 - Temperature increase and sea level rise for mitigation scenarios stabilizing CO_2 at 450ppm (left a,d), 400ppm (middle b,e) and 310ppm CO_2 (right c,f). Otherwise as Figure 4. The CO_2 equivalent concentrations in 2400 are about 500, 440 and 350ppm, respectively (cf. Figure 6). The underlying climate sensitivity PDF is based on the conventional 1.5°C to 4.5°C range (Wigley and Raper, 2001). The risk of overshooting 2°C is about 66% for the 500 CO_2eq scenario (panel a), 33% for a 440ppm CO_2eq scenario (b), and 33% around the peak and 2% in the long-term for the analyzed 350ppm CO_2eq scenario (cf. Table V for risks in equilibrium without natural forcing).

4.5 Risk of overshooting certain warming levels in equilibrium

The warming commitments shown for the scenarios extend to 2400 and are not the final warming of the system if these concentration levels are maintained (Watterson, 2003). It is instructive therefore to examine the final committed warming in equilibrium. Taking into account the uncertainty in the climate sensitivity, we present probabilistic results in terms of the risks that certain temperature thresholds (1.5°C to 3.5°C) are overshot (see Table V). The estimates we present here constitute a lower bound estimate, if stabilization levels are approached 'from above', i.e. after concentration peaked at higher levels before returning to the ultimate stabilization level (cf. Figure 7 c). For the higher stabilization scenarios, risk might be lower in practice, if concentration levels were not stabilized, but continuously decreased after 2100. This would prevent the full equilibrium warming from being realized. It should be kept in mind that natural forcings are here not taken into account (see section 3.5).

Given contemporary policy discussions around warming limits of 2°C (European Community, 1996; Caldeira et al., 2003) we focus here on the probability that committed warming will lie above 2°C for different long term stabilization levels given the uncertainty in the climate sensitivity.

From Figure 8, it can be seen that the choice of PDF for climate sensitivity uncertainty is quite fundamental in determining the probability of whether or not 2°C is already committed to for stabilization scenarios. The Knutti et al. (2002) and Gregory et al. (2002) PDFs with their long high tails imply the lowest probability to reach the 2°C target for the lower concentration levels. In contrast, the Forest et al. (2002b) estimate that is based on a confined expert a priori PDF suggests a narrower distribution and a lower mean estimate of climate sensitivity. Thus, according to the Forest et al. "expert prior" PDF, the risk of overshooting 2°C enters the "unlikely" range around 475ppm CO_2 equivalent stabilization level and is further reduced to "very unlikely" below the 410ppm CO_2 equivalent stabilization level[xix].

For stabilization of greenhouse gas concentrations at 550ppm CO_2 equivalent, (corresponding approximately to a 475ppm CO_2 stabilization), the risk of overshooting 2°C is very high, namely between 68%-99%, with a mean of 85% across the different climate sensitivity PDFs[xx]. In other words, the probability that warming will exceed 2°C could be categorized as 'likely' using the IPCC WGI Terminology. If greenhouse gas concentrations were to be stabilized at 450ppm CO_2 equivalent then the risk of exceeding 2°C were lower, but still significant, in the range of 26% to 78% (mean 47%). This could roughly be categorized as having a "medium likelihood". The 450ppm CO_2eq stabilization level would correspond roughly to the 400ppm CO_2 scenarios discussed above. Only for stabilization levels of 400ppm CO_2 equivalent and below, the possibility that warming of more than 2°C will occur, could be classified as "unlikely" (range 2% to 57% with mean 27%). The risk of exceeding 2°C in equilibrium is further reduced, namely to 0% to 31% (mean 8%), if greenhouse gases were stabilized at a 350ppm CO_2 equivalent level (see Figure 8).

Again, the question of how much risk of overshooting 2°C we are committed to primarily depends on the applied definition of a 'warming commitment'. Firstly, under a 'constant emission' scenario there is basically no chance (at best 2%, cf. Table V) to stay below 2°C in equilibrium. Secondly, the 'present forcing warming commitment' implies a 3% to 43% risk of overshooting 2°C – depending on the assumed climate sensitivity probability distribution function. When assuming the Murphy et al. (2004) climate sensitivity, the risk is about 8% and for the Schneider von Deimling et al. PDF approximation, the risk is basically zero. Thirdly, the 'geophysical warming commitment' with zero emissions does not entail any risks to overshoot 2°C in equilibrium, since it implies that radiative forcing levels will return to near pre-industrial levels in the long term. Fourthly, quantification of the 'feasible scenario warming commitment' again greatly depends on whether a 500ppm CO_2 equivalent or rather a 350ppm CO_2 equivalence scenario are considered the lowest feasible mitigation options. For the climate sensitivity PDF that is based on the conventional IPCC range (Wigley and Raper, 2001), the probability that we are committed to 2°C in equilibrium range from a medium likelihood (60%) to exceptionally unlikely (1%) (see Table V).

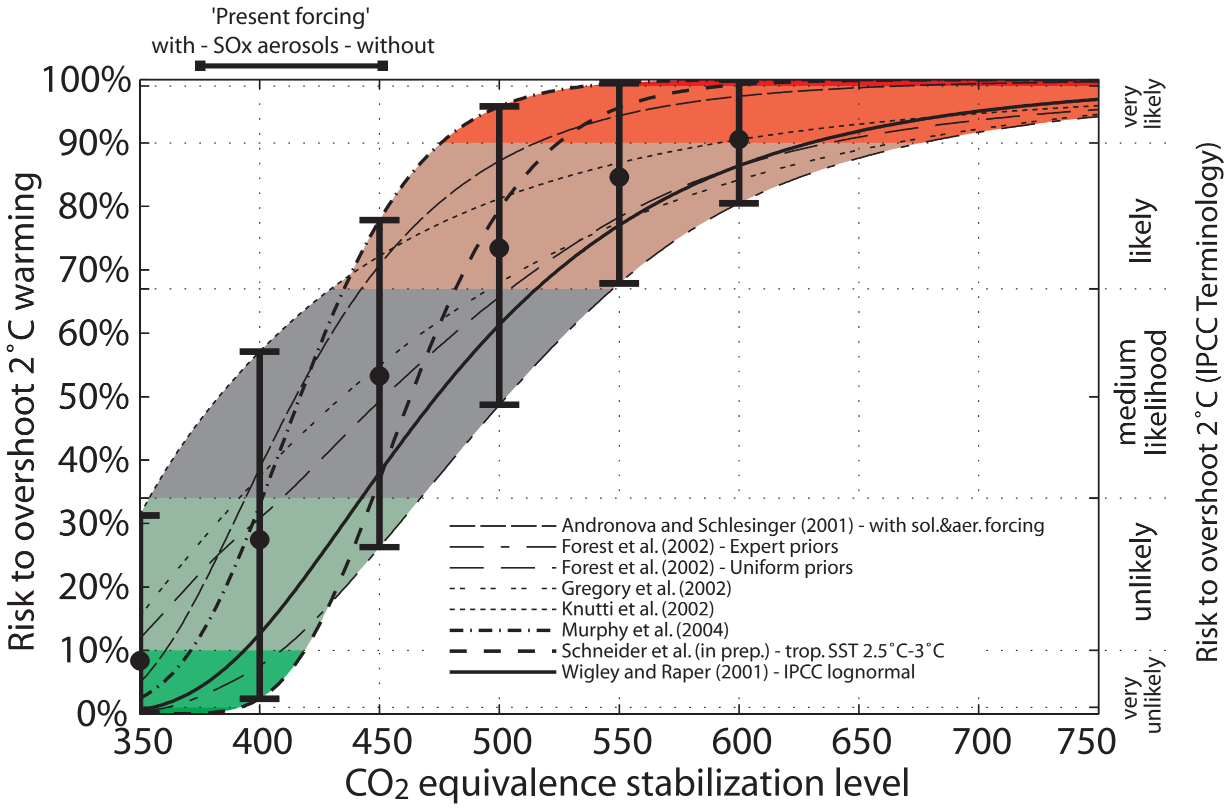

Figure 8 – Risk of overshooting a 2°C target. Current estimates of the climate sensitivity suggest that only by stabilizing anthropogenic radiative forcing at levels below CO_2 equivalent concentrations of 450ppm, the risk of overshooting the 2°C target can be termed "unlikely".

Table V - Risk of overshooting different global mean temperatures in equilibrium for the analyzed warming commitments (rows). In the first two rows, the CO_2, and CO_2 equivalent concentrations are given for 2400. The risk of overshooting a certain temperature limit in equilibrium (excluding natural forcings) is given for four climate sensitivity PDF estimates by 'Wigley' et al., 'Murphy' et al., 'Schneider' von Deimling et al. and 'Knutti' et al. (see section 3.3). Values in bold indicate risks of less then 33%, termed by IPCC as 'unlikely'. For example, only if future CO_2 equivalent concentrations are stabilized below 400ppm, overshooting 2°C in equilibrium is 'unlikely' (risk below 33%) for three out of the four climate sensitivity PDFs.

Warming commitment		1.Constant emissions	2.Present forcing	3.Zero emissions	4. Feasible scenarios			
					a	b	c	d
CO_2 in 2400 (ppm)		929	377	298	450	400	350	310
CO_2eq in 2400 (ppm)		899	368	282	500	440	385	350
Risk of overshooting warming level (%)								
>1.5°C	Wigley	100	**14**	**0**	87	65	**26**	**6**
	Murphy	100	37	**0**	100	97	60	**17**
	Schneider	100	**4**	**0**	99	84	**16**	**0**
	Knutti	100	59	**0**	91	82	66	50
>2°C	Wigley	99	**3**	**0**	60	**32**	**7**	**1**
	Murphy	100	**8**	**0**	95	69	**18**	**3**
	Schneider	100	**0**	**0**	78	**25**	**0**	**0**
	Knutti	98	43	**0**	81	69	50	**33**
>2.5°C	Wigley	96	**0**	**0**	34	**12**	**1**	**0**
	Murphy	100	**2**	**0**	73	**33**	**5**	**1**
	Schneider	100	**0**	**0**	**30**	**2**	**0**	**0**
	Knutti	95	**30**	**0**	70	57	38	**20**
>3°C	Wigley	87	**0**	**0**	**17**	**4**	**0**	**0**
	Murphy	100	**1**	**0**	43	**13**	**2**	**0**
	Schneider	99	**0**	**0**	**5**	**0**	**0**	**0**
	Knutti	91	**19**	**0**	61	47	**27**	**9**
>3.5°C	Wigley	75	**0**	**0**	**8**	**2**	**0**	**0**
	Murphy	99	**0**	**0**	**21**	**5**	**1**	**0**
	Schneider	95	**0**	**0**	**1**	**0**	**0**	**0**
	Knutti	86	**10**	**0**	52	38	**18**	**0**

4.6 Avoidable warming

Avoidable warming is computed here on the basis of paired comparisons of mitigation and non mitigation scenarios drawn from the range used in evaluating 'feasible scenario' warming commitments. Here we have compared the computed effects on global mean temperature between the SRES non-mitigation scenarios and the post SRES and/or WBGU 450 and 400ppm CO_2 mitigation scenarios. We compute the global mean temperature differences between the non-mitigation and mitigation scenario of the same scenario family until the year 2100. As a lower bound of the expected climate benefits, the 'current avoidable warming' indicates the warming difference in a specific year. The 'equilibrium avoidable warming' refers to the equilibrium warming difference (see Figure 10).

4.6.1 Current avoidable warming

The climate benefits of mitigation scenarios can be correlated to the mitigation effort, here indexed by the avoided cumulative fossil CO_2 emissions in any given year (see equation 3). The analysis shows that there is a significant temperature benefit (0.12-0.50°C) in most cases by 2050 based on the 7 AOGCM ensemble mean climate simulations (see Figure 9). The benefits increase to a range of 0.13°C-0.60°C for higher climate sensitivity (4.5°C) and decrease to a range of 0.10°C-0.33°C for lower sensitivity (2.5°C). Note that for the B1 IMAGE scenarios the 450ppm CO_2 scenario is *warmer* than the reference case by about 0.2°C, which is due to the reductions of sulphur emissions in the 450ppm CO_2 scenario (see 5.4).

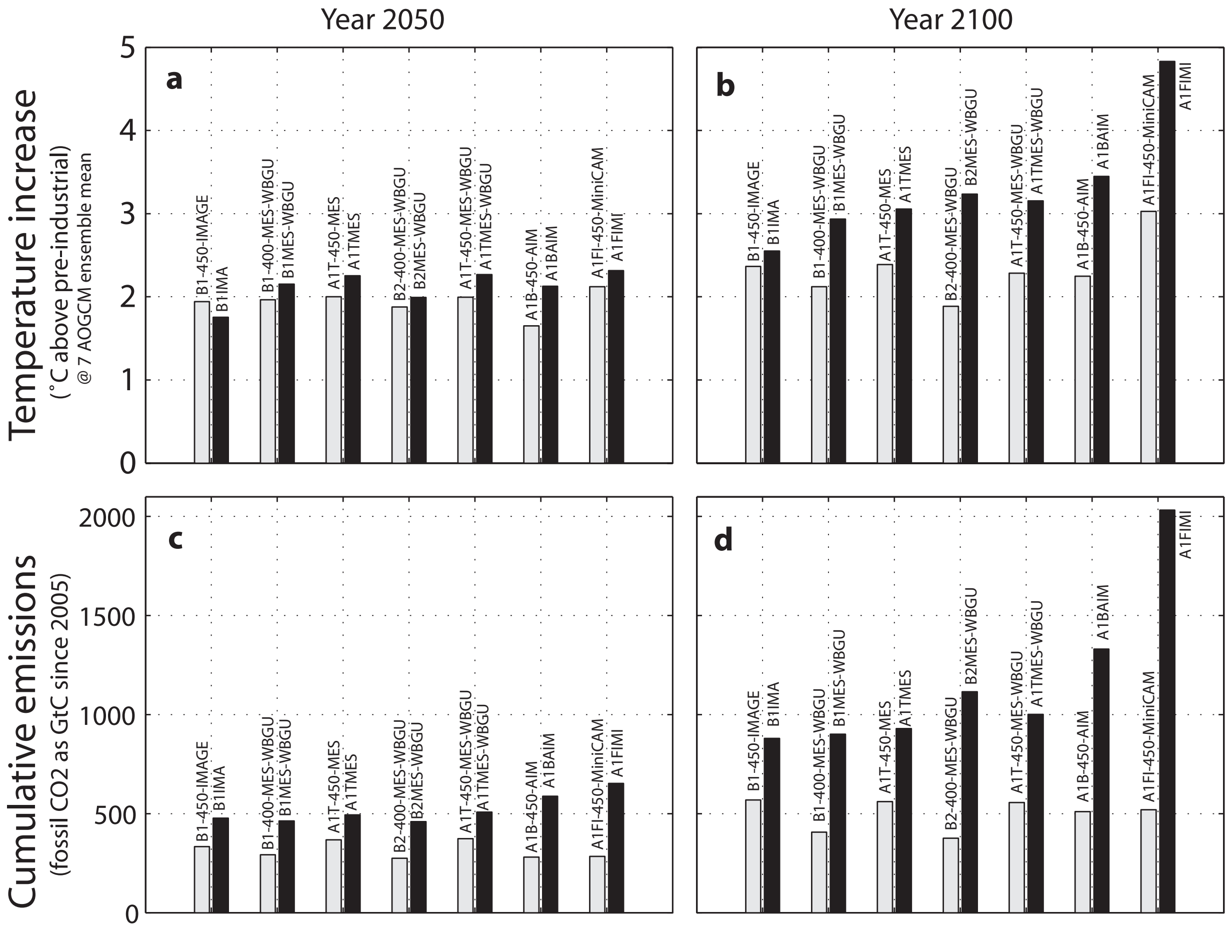

Figure 9 – Comparison of cumulative emissions and temperature increase for 2050 and 2100. The non-mitigation scenarios (black bars) have higher cumulative emissions (c,d) than the mitigation scenarios (grey bars). Consequently, the 'current' temperature increase up to year 2050 and 2100 is lower for almost all mitigation scenarios (cf. Figure 10). The '7 AOGCM ensemble mean' procedure has been applied here (cf. section 3.2).

It can be seen that as one goes further into the future the larger is the benefit of climate policy - with the benefit strongly associated with the scale of the mitigated emissions. In the '7 AOGCM ensemble mean' computations presented here, the avoided warming at any year is about 0.16 °C for each 100 GtC avoided cumulative fossil CO_2 emissions until that year (see equation 3). Thus, the analysis of existing multi-gas mitigation and non-mitigation scenarios suggests the following regression relationship for a climate sensitivity of about 2.8°C ('7 AOGCM ensemble mean') [xxi]:

$$\Delta T_{\text{year X}} = \frac{0.16°C}{100GtC} * \sum_{i=2000}^{yearX} \Delta E_i \qquad (3)$$

with

ΔEi : Difference in fossil CO_2 emissions in year i as index of the (multi-gas) mitigation effort.

$\Delta Tyear\ X$: Difference in temperature in year X

4.6.2 *Avoidable warming in the longer term*

Note that the 'current' avoidable warming relation is a conservative lower bound estimate of the climate benefits of mitigation. The avoided warming due to avoided fossil CO_2 emissions up to specific year X, e.g. 2050, 2075 or 2100, will grow beyond that year due to the inertia of the climate system. This effect is not fully captured by comparing avoided warming and avoided emissions for the same year, as presented in the previous section. Therefore, we present as well the equilibrium benefits. This equilibrium avoidable warming in any given year is computed as the difference in equilibrium warmings that correspond to the radiative forcing level in that respective year. A linear least squares regression across the scenario pairs suggests that 0.26°C warming can be avoided in equilibrium for every 100GtC of avoided fossil CO_2 emissions ('7 AOGCM ensemble mean'):

$$\Delta T_{\text{equilibrium}} = \frac{0.26°C}{100GtC} * \sum_{i=2000}^{yearX} \Delta E_i \quad (4)$$

with
ΔE_i : Difference in fossil CO_2 emissions in year i as index of the (multi-gas) mitigation effort.
$\Delta T_{\text{equilibrium}}$: Difference of equilibrium temperatures that correspond to radiative forcing levels in year X

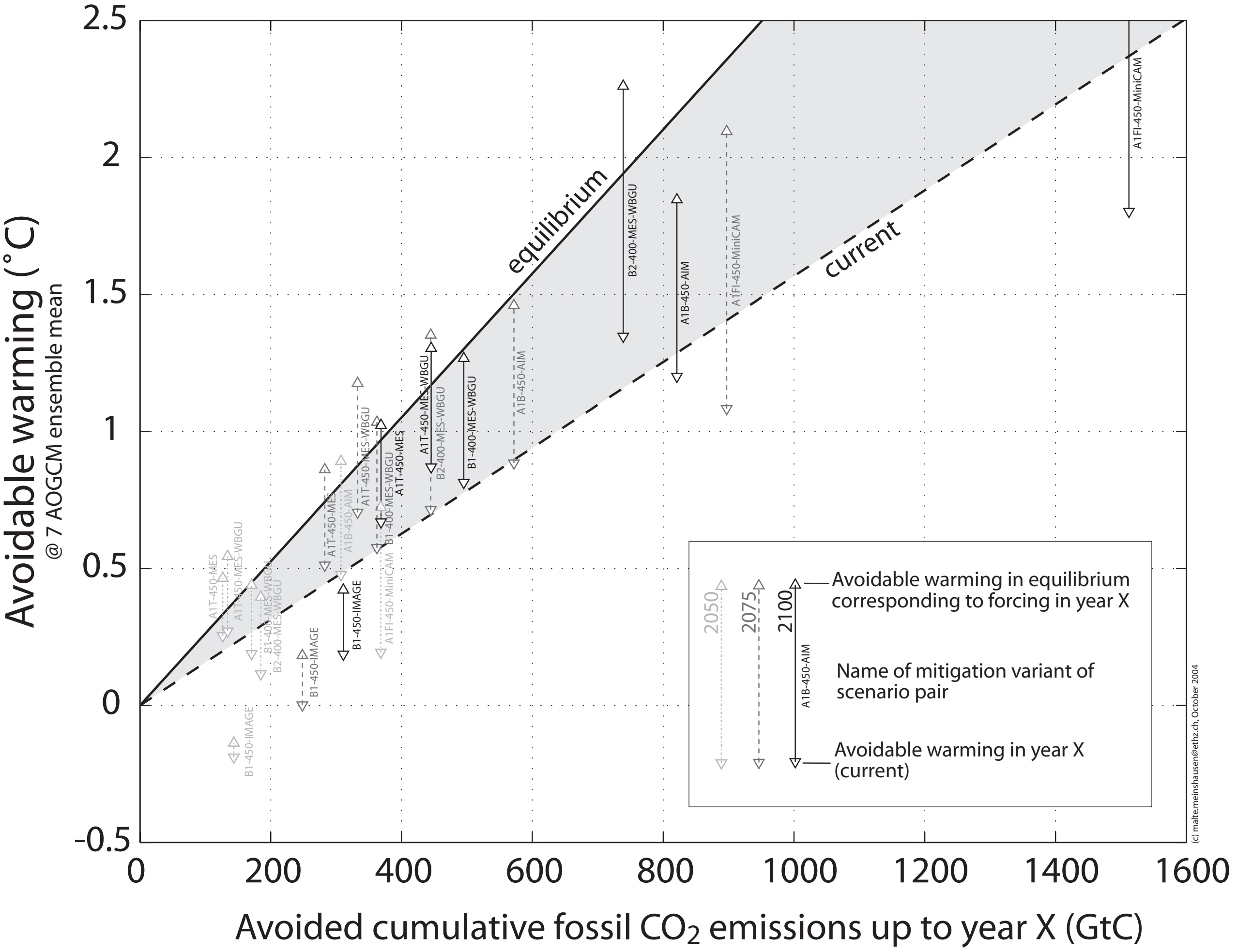

Figure 10 - Benefits of mitigation. Here paired comparisons between mitigation and non-mitigation scenarios of the same SRES scenario families are shown. The horizontal axis displays the mitigation effort in terms of the difference in cumulative fossil CO_2 emissions of a mitigation and non-mitigation scenario up to the year 2050, 2075 and 2100, respectively. The vertical axis displays the avoidable warming up to the year 2050, 2075 and 2100. See text for more details.

5 Discussion

In this section we turn to a discussion of the results and their implications for climate policy debates.

5.1 'Feasible scenario' warming commitments might underestimate avoidable warming

Several caveats indicate that the 'feasible scenario' warming commitments are probably an upper estimate on the committed warming.

The feasible scenario range we deploy here does not necessarily cover the full range of plausible possibilities for future emissions. The biomass energy carbon capture and storage technologies used in one of the 350ppm CO_2 scenarios (AZAR-350-BECS) could in principle draw down CO_2 in the atmosphere. This class of technologies appears feasible and the introduction rates could be accelerated compared to the rates deployed in the 350 ppmv CO_2 scenarios if there were sufficient political interest in doing so.

The scenarios generally do not include the full range of mitigation options known for agricultural and other sectors, particularly for non-CO_2 gases, and hence the temperatures calculated here are a bit higher (a few tenths of a degree) than might otherwise be the case[xxii].

Furthermore, increased mitigation efforts and hence lower concentrations than analysed here might become more plausible if scientific developments raises and broadens the perceived risk of large scale climate system singularities. Examples for potential thresholds are manifold, such as the potential decay of the Greenland ice sheet or the collapse of the West Antarctic, either of which have the capacity to raise sea level by some 5-6 meters on half millennial to millennial time scales in response to warming this century (Oppenheimer, 1998; O'Neill and Oppenheimer, 2002; Gregory et al., 2004; Oppenheimer and Alley, 2004; Thomas et al., 2004b). Other examples for potentially critical thresholds include a significant slow-down of the thermohaline circulation (Rahmstorf, 1999; Hansen et al., 2004), ecosystem risks, such as collapse of coral reefs (Hoegh-Guldberg, 1999), loss of biological hot spots or ecosystems with very high biodiversity values (Hannah et al., 2002; Midgley et al., 2002; Williams et al., 2003), or a threat of climate induced collapse of the Amazon rainforest (Cox et al., 2003; Cowling et al., 2004). In short, new scientific evidence and awareness of such potential thresholds is likely to change assessment of what is plausible policy action.

5.2 Extra warming due to delayed mitigation is likely to exceed the additional geophysical warming commitment

One of the issues that arises in climate policy is the climatic consequence of delay in taking action to limit emissions. The results presented here for the geophysical commitment calculations provide a way of quantifying a lower bound for the effect of delay on long term warming. These show that the effect of a 10 year delay in emission action commits to at least a further 0.2-0.3°C warming over 100-400 year time horizons. This is essentially a lower bound as emission reductions are very unlikely to exceed the complete cessation assumptions in these experiments. Also the geophysical warming commitment estimates neglect any technological or lock-in effects, if global emissions continue to rise unabated. Political, social, technical and infrastructural inertia is likely to multiply climatic costs that correspond to delays in mitigation action.

5.3 Time is running out for limiting warming below 2°C

The results can begin to provide an answer to the question "Under which emission scenarios is it still likely that we can achieve certain climate targets?".

The results suggest (see Figure 8) that we will have to return to present day net forcing levels (382ppm CO_2eq) or at least present greenhouse gas forcing levels (450ppm CO_2eq), if we want to limit global long-term temperature change to below 2°C with reasonable certainty. This analysis is based on the assumption that policies aim at *stabilizing* anthropogenic radiative forcing at a certain level. If radiative forcing were to decline, due to continuing emission reductions, the equilibrium warming implied by the peak concentration level would not be realized.

On the other hand, the lower mitigation scenarios used here overshoot their ultimate CO_2 equivalent stabilization levels in the 21st century. Thanks to the inertia of the climate system, the equilibrium temperature corresponding to the peak concentrations will not be felt. However, the results suggest that if the ultimate stabilization level is below 450ppm CO_2eq, the initial peaking level around 2100 seems to be the decisive characteristic for determining the maximum temperature increase (cf. Figure 7). The peaking concentration in turn will be the main determinant behind emission reduction needs in the coming years and decades (see Table VI).

In any case, it becomes clear that pronounced emission reductions are needed globally in order to limit with a reasonable certainty the risk of overshooting 2°C. At 2050, global greenhouse gas emissions have to be decreased by 30% to 50%, or at least 20% (if net *negative* CO_2 emissions of -3.6 GtC/yr by 2100 can be envisaged achievable thereafter, AZAR-350-BECS). The lower range of mitigation scenarios presented here are likely to be relevant to the operationalization of Article 2 of the UNFCCC which calls for the prevention of dangerous interference with the climate system. Especially those mitigation scenarios will be important for that attempt to continuously lower global mean temperatures after peaking as "returning to near pre-industrial global temperatures as quickly as possible could prevent much of the projected, but slower acting, climate-related extinction from being realized" (Thomas et al., 2004a). This would also apply to a reduction in the risk of West Antarctic Ice Sheet disintegration or collapse triggered by either atmospheric or ocean warming (Oppenheimer and Alley, 2004).

Table VI – Global emissions relative to 1990 for the analyzed mitigation scenarios. The 'all GHGs' columns comprise CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6. Values are bracketed for the CO_2-only AZAR scenarios that have been complemented by non-CO_2 emissions from B2-400-WBGU. In addition, the first two columns indicate the risk of overshooting 2°C in equilibrium and at peaking temperature values based on transient runs (roughly around 2100 for the lower 6 scenarios – cf. Figure 7). Only the lower stabilization scenarios have a "unlikely" risk of overshooting, although their overall risk from transient runs might be higher than the risks in equilibrium. The lognormal climate sensitivity PDF base on the conventional 1.5°C to 4.5°C IPCC uncertainty range has been applied here (Wigley, 1998) (cf. Table V).

	Risk > 2°C equilibrium	Risk > 2°C ~2100	Global emissions relative to 1990 (%)					
			all GHGs			fossil CO_2 only		
Mitigation scenario	(Wigley)	(Wigley)	2020	2050	2100	2020	2050	2100
B1-450-IMA	60%	~60%	127%	100%	46%	138%	102%	53%
A1T-450-MES	60%	~60%	122%	102%	54%	149%	107%	45%
A1B-450-AIM	60%	~60%	101%	102%	75%	103%	96%	65%
A1T-450-WBGU	60%	~60%	115%	107%	49%	125%	113%	31%
A1FI-450-MI	60%	93%	126%	120%	102%	119%	84%	94%
B2-400-WBGU	**32%**	**33%**	111%	66%	42%	121%	42%	26%
B1-400-WBGU	**32%**	50%	110%	69%	41%	120%	56%	27%
AZAR-350-FC	**7%**	**10%**	(80%)	(51%)	(28%)	67%	16%	1%
AZAR-350-NC	**7%**	**10%**	(87%)	(49%)	(28%)	80%	13%	1%
AZAR-350-BECS	**1%**	**33%**	(107%)	(78%)	(-5%)	115%	64%	-57%

5.4 Reducing emissions: health benefits from reduced aerosols dominant in first 30 years, then temperature benefits kick in.

The committed warming, or level of warming that is avoidable, also depends on the residence times of the atmospheric radiative forcing agents. Aerosols have a short lifetime (months to 1 or 2 years). Reductions in aerosols (which have a negative radiative forcing) and other air pollutants, such as those leading to tropospheric ozone formation (with a substantial positive radiative forcing) can lead to large net changes in forcing quite quickly. Changes in CO_2 forcing, which are partly shaded by the aerosol effect, will happen much more slowly and the effects of past emissions will survive much longer in the atmosphere. The net effect is that policies that reduce both air pollution (aerosols) and CO_2 may result in more warming in the short term (decades), whilst reducing warming in the longer term (see Figure 3, Figure 10 and cf. Wigley (1991)). Hence the avoidable warming in the short term may not be as great as sometimes assumed. Numerous impact studies indicate benefits in several impact categories arising from mitigation scenarios with emission corresponding to stabilization at 550ppm CO_2 as opposed to the IS92a reference case (Parry et al., 2001; Arnell et al., 2002). The robustness of these results needs to be further examined to take into account actual sulphur emissions and other air pollutants that affect tropospheric ozone levels, for example. Sulphur emissions might already be lower than assumed in the post-SRES and SRES scenarios (Streets et al., 2001). This means that some of the additional temperature increases in the first decades of the 20th century resulting in the mitigation scenarios from sulphur emission reductions arising from reduced fossil fuel emissions would not occur. This may have the effect of enhancing the benefits of climate policy on a 2020s or 2030s time scale. On the other hand, reactive gas emissions, which lead to tropospheric ozone formation that adds positively to radiative forcing may be less than assumed as well, reducing the apparent benefit of mitigation (Wigley et al., 2002). By the time of the 2050s, there is however a clear difference between mitigation and non-mitigation scenarios, up to 0.5°C for the A1B scenarios (see Figure 1).

5.5 Precautionary approach needed until key climate sensitivity uncertainty better understood.

There are several key features of the climate system that are relevant to the question of committed and avoidable warming. Many of them are summarized in the key parameter 'climate sensitivity'. The climate sensitivity strongly affects estimates of the warming and sea level rise to which we are committed. Firstly, the higher the sensitivity, the higher is the ultimate warming commitment for a given emissions pathway. Secondly, the range of warming implied by a fixed range of climate sensitivity can grow or shrink over time, depending on whether radiative forcing increases or decreases, respectively (see Figure 4) [xxiii]. This illustrates the simple fact that the more we move away from pre-industrial greenhouse gas levels, the more uncertain we are about the absolute climate system response.

As can be seen from the range of results in Figure 2 there is a large uncertainty in this key parameter, which is of quite fundamental significance for policy. Some narrowing of the uncertainty range could be inferred from the results of Schneider von Deimling et al. (see Kerr, 2004), particularly the ruling out of climate sensitivities higher than 4°C and lower than 1.5°C on the basis that sensitivities outside this range are inconsistent with what is known of the Last Glacial Maximum (about 21'000 years ago) climate. However, several factors militate against a strong conclusion here. By restricting the scale of climate system feedbacks that operated in the past, there still remains a significant uncertainty about how climate system feedbacks will operate in the future in a warmer world. Furthermore, there are a couple of concerning feedbacks that are not summarized within the 'climate sensitivity' indicator, since they actually change the greenhouse gas concentrations, not the relative climate response to it. For example, potentially large carbon cycle feedbacks or releases of methane hydrates would add to the need for more pronounced mitigation action (see next section). More research will assist in narrowing uncertainties. However, as is recognised in Article 3.3 of the UNFCCC, a precautionary approach to this key uncertainty is needed.

5.6 Possible underestimation of the warming and sea level rise commitment for a particular emission scenario

Another limitation of these results is that the large uncertainties in the carbon cycle's feedback or potential methane hydrate releases (Archer et al., 2004); (Buffet and Archer, in press) to temperature increases are not taken account of. Large terrestrial carbon cycle feedbacks for example, as found in some models (Jones et al., 2003a; Jones et al., 2003b) would imply higher concentrations for the same level of anthropogenic greenhouse gas emissions. Thus, large carbon cycle feedbacks might significantly increase the need for decisive mitigation efforts, if certain greenhouse gas concentrations and corresponding temperature levels should not be overshot.

5.7 Climate system inertia acts on multiple time scales.

Like a large ship, it takes the climate system a long time to fully respond to the effects of changes in 'external' forcing, such as increased levels of greenhouse gases. As it becomes apparent from the presented results, the climate responds to forcing changes on all timescales (see as well Shindell et al., 2004). A large part of the atmospheric response to forcing changes is on decadal timescales (Hooss et al., 2001) but a substantial component is linked to the long, century time scales of the oceanic response to forcing. The different time scales of the response of different components of the climate system (ocean, atmosphere, carbon cycle) means that the inertia of the system will be different for different parts of the system for the same forcing changes.

The different response scales become clearest in relation to steric sea level rise and changes in the surface climate over land. The former is dominated by very long time scales and hence has large inertia (see e.g. Figure 3 and Figure 4). Sea level rise caused by the gradual penetration of heat into the deep ocean, as the climate system comes slowly into equilibrium with the human disturbance, will continue for many thousands of years (IPCC, 2001c, p. 17). As can be seen from Figure 3 d and Figure 4 e), in a purely geophysical sense, there seems to be a commitment to further unavoidable sea level rise, and only its rate of increase can be limited[xxiv]. To limit sea level rise below the geophysical commitment, and to lower the temperature faster, would require technologies for capturing CO_2 from the air and storing it in geological reservoirs or other geo-engineering techniques which themselves bear large risks (Govindasamy et al., 2003). Surface climate will respond much more quickly than sea level to changes in radiative forcing, but the time scales are still very long, of the order of many centuries.

Owing to the slow response of the deep oceans to the effect of added greenhouse gases, the climate systems will continue to adjust to the effects of these changes, even once greenhouse gas concentrations or radiative forcing are stabilized, for a very long time. In addition to other feedbacks over long time scales, this suggests an effectively increasing climate sensitivity over time (Senior and Mitchell, 2000), which is not captured within the model used in this study. However, after stabilization of greenhouse gas concentrations the rate of temperature increase slows substantially: "only few tenths of a degree per century rather than several degrees per century as projected for the 21st century without stabilisation." (IPCC, 2001c, p. 17).

Another important aspect of the climate system for the assessment of its inertia in relation to the effects of forcing changes is that that the lag between the surface warming and the forcing is longer with higher climate sensitivity. Although not fully explained physically it appears to be quite a robust property of the system (Hansen et al., 1985; Raper et al., 2002).

5.8 Possible underestimation of the cooling rate for scenarios with reducing radiative forcing.

A limitation of the applied climate model and hence the presented results is its symmetric response to positive and negative radiative forcing. The climate system responds faster to a reduction in forcing than to an increase, due to the physics of the ocean response to forcing changes. In other words, the climate system at the global level is likely to cool faster than it warms. For a warming climate the ocean becomes more thermally stratified and hence deeper mixing slows relatively, and for a cooling climate, with declining radiative forcing, this thermal stratification is reduced and hence the response is faster. Hence if radiative forcing declines then at the global level, the response to a reduction in forcing will be faster than when radiative forcing was increasing (Stouffer, 2004). These processes are likely to be important in the latter parts of the 21st century and beyond in relation to climate policy aimed at preventing dangerous changes in the climate system. However, this effect is not captured in the upwelling-diffusion ocean model in MAGICC 4.1 as it responds symmetrically to warming and cooling. Thus, the rate of cooling for the geophysical warming commitment and the lower mitigation scenarios might actually be faster than presented here (see Figure 3, Figure 5 and Figure 6).

5.9 Ultimate warming commitment bound from below by slow permanent CO_2 sink at ocean floor.

The long atmospheric residence time of CO_2 and long-lived halogenated compounds has a significant impact on the committed long-term warming and sea level rise. Anthropogenic carbon dioxide emissions are taken up by the terrestrial biosphere and the oceans at first relatively rapidly. Mid range carbon cycle model such as that used in MAGICC indicate that after a century about 30% of unit emissions made at present would remain in the atmospheres and after about 500 years 15% would remain. In the longer term however the uptake is governed by slow processes at the ocean floor so that after 5,000 years about 10% of present emissions would still remain in the atmosphere (Archer et al., 1997; Archer et al., 1998). This implies a significant future commitment arising from contemporary emissions patterns over multi-millennial time scales even if all emission ceased. For example even if emissions were to cease in the next few years, CO_2 levels would remain above the highest levels that have prevailed over the last 420,000 years before the present historical period for the next 10,000 years[xxv].

6 Conclusions

There is no single scientific assessment that can be made of a 'warming commitment'. If global human-induced greenhouse gas and aerosol emissions were to cease immediately temperature would continue to increase, but then begin dropping rapidly after a decade before slowly returning to temperatures characteristic of the mid 20th century by the end of the 22nd century, namely to 0.3°C – 0.5°C above pre-industrial levels. The main insights that one can derive from the zero emissions scenario is that there is a floor to how fast temperatures can drop in the long term (in the absence of negative emissions). Furthermore, it shows that there is a likelihood that sea level rise cannot be halted, only slowed substantially.

It is clear from the analysis here that the 'feasible scenario warming commitment' for the period to 2100 depends significantly upon the assumed emission mitigation scenarios. Therefore, transparency is warranted in regard to the token socio-economic assumptions in each mitigation scenario. If one believes that the most rapid feasible CO_2 reduction scenario in the literature cited above is plausible (Azar et al., submitted) then the peak temperature during the 21st century is around 1.6-1.7°C and this declines to around 1.5-1.6°C warming above pre-industrial by 2100, for the '7 AOGCM ensemble mean'. On the other hand, if one believes that the maximum plausible policy effort corresponds to the B2 WBGU 400ppm CO_2 stabilization scenarios then warming at the end of the 21st century would be around 1.9°C or a bit lower when additional policies and options to reduce non-CO_2 gases were accounted for. If 450ppm CO_2 scenarios correspond to one's assessment of the maximum plausible climate policy then the warming by 2100 is limited to about 2.2-2.4°C.

Uncertainties in knowledge of the climate sensitivity warrant probabilistic assessments of warming commitments for specific scenarios. The conventional uncertainty range of climate sensitivity (1.5°C to 4.5°C) suggests that only by stabilizing anthropogenic radiative forcings at levels below CO_2 equivalent concentrations of 440ppm (CO_2 only below 400ppm) is there more than a 66% chance of limiting the global mean temperature increase to below 2°C. Four out of the 7 more recent climate sensitivity PDF estimates suggest that CO_2eq concentrations have to be even lower in order to have a "likely" chance of achieving a 2°C target, namely below 400ppm CO_2eq in equilibrium (see Figure 8).

The scenario range above does not necessarily cover the full range of possibilities. For example the biomass fuel with carbon capture and storage technology used in the Azar et al. (submitted) scenarios, which essentially would draw down CO_2 in the atmosphere, could be accelerated if it were deemed necessary. Such a necessity might arise if critical climate thresholds were identified and it was generally agreed that these should not be crossed. Whilst there is no agreement at present on such thresholds, scientific progress points in the direction of the existence of these, which - if confirmed - could sooner or later yield to political agreement given the scale of the physical dangers.

In relation to warming commitments in the period to the 2050s it is clear from the analysis here that there are significant benefits in terms of reduction in global mean warming available from mitigation scenarios. The benefits depend on the reference scenario – the higher the reference scenario the greater is the benefit of the mitigation scenarios examined here. For the '7 AOGCM ensemble mean', the avoidable warming in a given year is found to be about 0.16°C for every 100GtC avoided cumulative fossil CO_2 emissions up to that year. The ultimate benefit of mitigation efforts will be higher, though, about 0.26°C for every avoided 100GtC fossil CO_2 emissions in equilibrium.

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Endnotes

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[i] Own calculations based on data from (Folland et al., 2001; Jones and Moberg, 2003), available at: http://www.met-office.gov.uk/research/hadleycentre/CR_data/Annual/land+sst_web.txt, accessed 15. October 2004.

[ii] Furthermore, it should be considered that from a health policy point of view, continued high aerosol emissions are not desirable. However, high aerosol emissions would be a temporary effect of a strict 'constant radiative forcing' scenario. Radiative forcing stabilization scenarios that return to present day levels of radiative forcing in the future can be constructed with much reduced aerosol emissions.

[iii] The Post-SRES scenarios used here are presented in Swart et al. (2002). See as well (Morita et al., 2000; and figure 2-1 in Nakicenovic and Swart, 2000). Selection is due to data availability.

[iv] MAGICC 4.1 has been developed by T.G.L. Wigley, S. Raper and M. Hulme and is available at http://www.cgd.ucar.edu/cas/wigley/magicc/index.html, accessed in May 2004.

[v] This improvement of MAGICC only affects the no-feedback results. When climate feedbacks on the carbon cycle are included, the differences from the IPCC TAR are negligible.

[vi] Additional estimates of the climate sensitivity and their likely ranges have for example been performed by Harvey and Kaufmann (2002). However, adding more estimates to the analysis would not have added to the substance of the discussion below.

[vii] Note, that the conventionally cited 'combined pdf' from Andronova & Schlesinger (Andronova and Schlesinger, 2001) has been combined from estimates that do not take into account aerosol forcing or variations in solar radiation. Therefore, it is not displayed here.

[viii] The work of Thomas Schneider von Deimling, Hermann Held, Andrey Ganopolski, Stefan Rahmstorf (in preparation) at the Potsdam Institute of Climate Impact Research (PIK) has sought to estimate climate sensitivity using the Climber 2 model constrained by estimates of climate cooling during the last glacial, changes in climate forcing in this period and with climate change during the historical period. The estimate shown is a best estimate based on a best guess of the glacial cooling of the tropical sea surface in the range 2.5-3°C. At present a formal probability density function has not been estimated and here a log normal distribution is assumed. These results should be regarded as preliminary and subject to change.

[ix] The alternative, to leave natural forcings out in the future, is not really viable, since the model has been spun up with estimates of the historic solar and volcanic forcings. Assuming the solar forcing to be a non-stationary process with a cyclical component and assuming that the sum of volcanic forcing events can be represented as a Compound Poisson process, it seems more realistic to apply the recent and long-term means of solar and volcanic forcings, respectively, for the future.

[x] Note that there are corresponding slight variations in CO2 concentrations across the different climate sensitivities due to climate feedbacks on the carbon cycle. For a climate sensitivity of 1.5°C (4.5°C), CO2 concentration in 2400 will be 900 (960) ppm.

[xi] Note that the Hadley centre uses the term 'current physical commitment' for what is termed 'present forcing warming commitment' in this study.

[xii] The GFDL R15 model of (Manabe et al., 1991) was used and has a climate sensitivity in its mixed layer form of 3.7°C and in the full coupled version 4.5°C (Stouffer and Manabe, 1999). The committed warming has been calculated as the year 2000 difference of the mixed layer equilibrium model run and the transient AOGCM.

[xiii] This warming is the total reported from the equilibrium mixed layer (EML) model from 1760 and adjusted downwards by 0.2°C in order to ensure consistency with the here used base period from 1861-1890 (cf. Figure 1 of Wetherald et al, (2001).

[xiv] Note that there is significant uncertainty in regard to the aerosols' cooling effect. This greenhouse gas only CO_2 equivalence level has been derived from the 2005 radiative forcing when running the SRES A1B emission scenario with zeroed SO_2 emissions under the '7 AOGCM ensemble mean' procedure.

[xv] One potential technique for increasing the rate of CO2 removal from the atmosphere beyond its natural limits could be biomass burning with subsequent capture and storage of CO2 in the flue gas (Azar et al., submitted).

[xvi] The long-term implications for sea-level rise need to be further explored using complex ocean models as opposed to the simple upwelling diffusion model in MAGICC 4.1. However, the overall sense of inertia is clear: sea level rise due to thermal expansion will be very difficult to stop.

[xvii] As aforementioned (section 2.4), the non-CO2 emissions for the Azar scenarios are here drawn from the WBGU B2-400 scenario. Thus, temperature levels in 2100 could be slightly lower by a few tenths of a degree, if additional non-CO2 emission reductions were assumed below the ones of the WBGU B2-400 scenario.

[xviii] The 'Equal Quantile Walk' method allows designing new emission pathways on the basis of a large pool of existing scenarios. The basic premise of the method is to assume that each gases emissions' of the new mitigation pathways will lie on the same 'quantile' of the existing pool's emission distribution of the specific gases in any given year (see the method in detail described in Meinshausen et al., submitted).

[xix] If not otherwise noted, this study follows the terminology introduced by the IPCC TAR WGI for presenting likelihoods in its Summary for Policymakers: Virtually certain (>99%), very likely (90%-99%), likely (66%-90%), medium likelihood (33%-66%), unlikely (10%-33%), very unlikely (1%-10%), exceptionally unlikely (<1%).

[xx] Note that the reported probability *means* are presented for illustrative purposes only. Since the climate sensitivity estimates are not independent the presented means are of little statistical relevance. In other words, the choice to characterise these results by their means has been made subjectively.

[xxi] Note that the regression factor (0.16°C/100GtC) cannot be simply scaled by the climate sensitivity due to the generally higher climate system inertia for higher climate sensitivities. Approximately, the regression factor can be scaled by the square root of the climate sensitivity, though. The regression factor has been derived by linear least-squares. The A1FI-MiniCAM scenarios were exempted, though, as the avoided warming falls far outside the range of the other scenarios and would thereby unduly influence the regression.

[xxii] In the post SRES scenarios, including the WBGU variants, the non-CO2 gases were not explicitly calculated except in so far as reductions occurred linked to change in fossil fuel emissions. Reductions in other sectors were usually not computed.

[xxiii] Note however, that the shown shrinking of the warming range in Figure 4, derived with a simple climate model, might be moderated by the asymmetric response of the climate system to a cooling and warming (see section .5.8)

[xxiv] The continued sea level rise could be an artefact of the upwelling diffusion model used which responds symmetrically to warming and cooling. The oceans are likely to respond asymmetrically to cooling and warming (Stouffer, 2004), hence the rate of rise at least may be exaggerated. This would need to be explored with more complex models and would also have implications for plausible scenarios involving declining radiative forcing.

[xxv] Estimated using the following assumptions: (a) emissions from fossil fuels and deforestation in the historical period to the present are 450 GtC and (b) the time scales of removal are those reported by Archer et al (1997; 1998) and (c) CO2 did not exceed 280-290ppm throughout the last 420'000 years.

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