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 2002 global mean temperatures were $0.8 \pm 0.2\,^{\circ}$C above the pre-industrial (1861–1890) 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? Using a simple climate model (MAGICC) for probabilistic computations based on the conventional IPCC uncertainty range for climate sensitivity (1.5 to 4.5 °C), we found that (1) a 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) For the present radiative forcing levels it seems unlikely that 2 °C are overshoot. (central warming estimate 1.1 °C by 2100 and 1.2 °C by 2400 with ∼10% probability of overshooting 2 °C). However, the risk of overshooting is increasing rapidly if radiative forcing is stabilized much above 400 ppm CO_2 equivalence (1.95 W/m^2) 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 (350 ppm CO_2eq to 450 ppm CO_2eq) provides the central temperature projections are 1.5 to 2.1 °C by 2100 (1.5 to 2.0 °C by 2400) with a risk of overshooting 2 °C between 10 and 50% by 2100 and 1–32% in equilibrium. Furthermore, we quantify the 'avoidable warming' to be 0.16–0.26 °C for every 100 GtC of avoided CO_2 emissions – based on a range of published mitigation scenarios.

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 we are committed to, and what can be avoided, has a major bearing on issues such as the benefits of climate policy and to decisions relating to

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Article 2 of the UNFCCC, which is the obligation to prevent dangerous interference with the climate system. For example, as a first step to operationalize Article 2 of the UNFCCC the Heads of Government of the European Union have confirmed a global goal of not exceeding a warming of 2 °C above pre-industrial levels.[1] With global mean temperatures in 2002 estimated to be 0.8 ± 0.2 °C[2] above the pre-industrial mean (1861–1890) (Folland et al., 2001; Jones and Moberg, 2003)[3] 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 global mean temperature response is insensitive to differences in SRES non-mitigation emission 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'. 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; Wigley, 2005). 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; Meehl et al., 2005; Wigley, 2005). 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 analyse two others. The first we term the 'geophysical warming commitment', which is the warming commitment resulting after an abrupt and complete cessation of anthropogenic emissions. This captures the change in temperatures that results solely from the operation of geophysical and chemical processes on the burden of greenhouses gas and other forcing agents in the atmosphere without consideration of inertia in human, social and economic systems. Due to the inertia in these latter systems it is assumed that an abrupt and complete cessation is infeasible from any economic, human and social point of view, hence this is an idealized geophysical thought experiment. 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, there are several difficulties and inconsistencies with applying this concept beyond a thought experiment. The time horizon over which the emissions are held constant more or less determines the warming commitment, which would continue to rise with emissions. Whilst even over very long time horizons (millennia) maintaining constant emissions would appear feasible as fossil fuel resources are potentially quite large when account is taken of conventional and unconventional reserves, including methane hydrates, these sources of CO_2 would ultimately run out. A further problem with this concept 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.

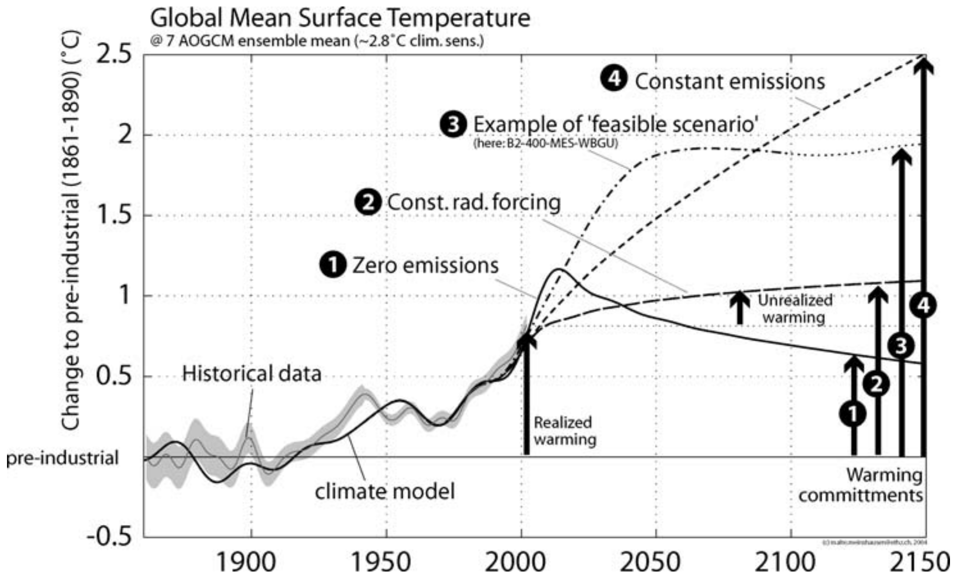

Figure 1. Four different types of warming commitments. (1) The 'geophysical' warming commitment in case that emissions are abruptly reduced to zero after 2005 ('Zero Emissions'); Note that emissions initially rise due to ceased cooling by aerosols. (2) The 'present forcing' warming commitment corresponds 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).

2.2. PRESENT FORCING COMMITMENT

This is defined here as the warming 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 (Hansen et al., 1985) that corresponds to present day composition of the atmosphere and its radiative forcing levels. Hence, this commitment can as well be termed the "constant-composition" commitment (Wigley, 2005).[4]

The actual present day radiative forcing is rather uncertain mainly due to uncertain contribution of aerosols. Central estimates range between 1.7 W/m^2 (Wigley, 2005), or 1.55 and 1.1 W/m^2, if individual radiative forcing estimates given by Hansen et al. (2000) or IPCC TAR are convoluted to a net forcing estimate. If today's net radiative forcing is constrained by consistency tests with historic temperature observations a central estimate between 1.25 to 2.5 W/m^2 seems likely

(Knutti et al., 2002). This study uses a net radiative forcing (human-induced & natural) of 1.93 W/m^2 for 2005 relative to the 1861–1890 period, of which 0.67 W/m^2 is due to natural forcing increases since 1861–1890.[5]

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.[6] 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 in general, although it is sometimes interpreted that way. A scenario that has low emissions in the 21st century and beyond could produce warming levels that approach or drop below the levels implied in a constant radiative forcing scenario (see Figure 6c).

2.3. GEOPHYSICAL COMMITMENT

A warming commitment can be defined from a purely geophysical perspective, as the warming that would result after 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. The term geophysical is used here in the sense that following the cessation of emissions, the time path of warming is determined solely by the operation of the biogeophysical components of the climate system assimilating the effects anthropogenic perturbations to atmosphere without further human intervention. The time path of warming is influenced to a small degree by the assumed natural forcings (solar irradiance and volcanic eruptions) relative the preindustrial period, but this does not fundamentally affect the estimates.

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 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 presently 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 450 ppm 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 450 ppm CO_2 stabilization scenarios.[7] In addition, we use recent scenarios for a CO_2 stabilization at 400 ppm 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 350 ppm (Azar et al., in press) 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, as discussed in Section 5.1.

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 under a non-intervention scenario. 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).

3. Method

This section entails a brief description of the simple climate model MAGICC employed in this work (3.1). In the non probabilistic components of this work we use a standard '7 AOGCM ensemble mean' (7AEM) 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.[8] 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), Wigley et al. (2002) and (Wigley, 2005). Additional details are given in the IPCC TAR climate projections chapter 9 (Cubasch et al., 2001). 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).[9]

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).

3.2. 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' (7AEM) procedure, which we will hereafter refer to as 7AEM, is widely used in the IPCC Third Assessment Report and described in Appendix 9.1 (Cubasch et al., 2001). By using this 7AEM 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 7AEM 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 CO_2 concentrations, e.g. doubling of pre-industrial levels ($2 \times 278 = 556$ ppm). 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 function 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). Specifically, we sampled climate sensitivity at the quantiles of interest, namely 1, 5, 10, 33, 50, 66, 90, 95 and 99% of the PDFs (cf. Figures 4 and 7).

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. 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. Neglecting uncertainties in ocean mixing, specifically the likely lower ocean

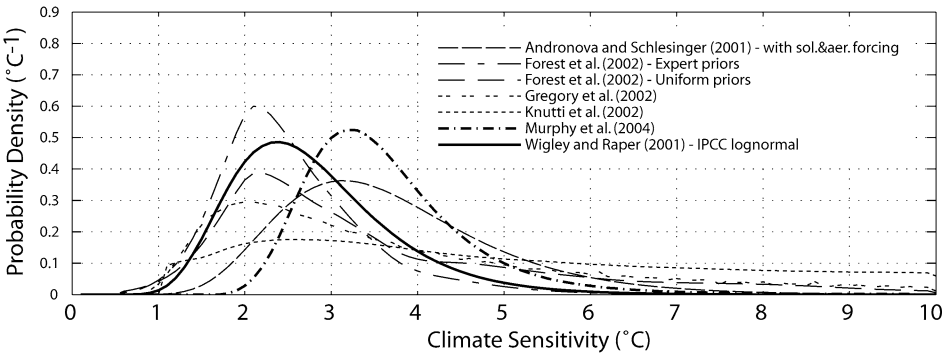

Figure 2. Different estimates of the probability density functions for climate sensitivity.

mixing rates for lower climate sensitivities, might have relatively limited effects though.[10]

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 to 4.5 °C.

After the completion of the IPCC TAR, a number of estimates of the climate sensitivity have been published each with its own strengths and weaknesses (see e.g. IPCC, 2004). Seven of these estimates are used in the subsequent analysis and shown in Figure 2[11]: Six studies have attempted objective estimation of a probability density function (PDFs) for climate sensitivity 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;[12] (2–3) estimates by Forest et al. (2002) 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-member ensemble of an atmosphere GCM, HadAM3, coupled to a mixed layer ocean model to enable integrations to equilibrium (Murphy et al., 2004). (7) The seventh estimate is drawn from the conventional 1.5 to 4.5 °C IPCC uncertainty range with a pdf constructed by Wigley and Raper (2001). This estimate assumes that the distribution is log-normal with the IPCC range being taken as the 90% confidence range. This can be seen as an attempt to codify the expert judgement character of the IPCC assessments, but, as is emphasized by Wigley and Raper (2001) does not represent either the full range of uncertainty or some "best estimate" based on all other estimates.

In the following work we have used all of the pdfs described above and to illustrate some of our results we have chosen to focus on the PDFs (5) to (7) as they 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). PDFs (5) and (6) are based on the recent period but have very different shapes, PDF (7) is roughly similar to the Forest et al. (2002) expert prior estimate but has the virtue for the discussion of results here that it codifies the expert assessment of the IPCC.

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) (W/m^2) follows the logarithmic equation:

$$\Delta Q = \alpha \ln\left(\frac{C}{C_0}\right) \tag{1}$$

where α is 5.35 W/m^2 and C_0 the unperturbed pre-industrial CO_2 concentration level (278 ppm), based on Myhre et al. (1998). The equilibrium temperature is then assumed to scale linearly with radiative forcing:

$$\Delta T = \Delta Q \frac{\Delta T_{2\times CO_2}}{\alpha \ln(2)} \tag{2}$$

where $\Delta T_{2\times CO_2}$ (K) is the climate sensitivity and $\alpha \times \ln(2)$ 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 greenhouse gases, tropospheric ozone, and aerosols but not natural forcings.

3.5. NATURAL FORCINGS

Historic solar and volcanic forcings estimates have been assumed, according to Lean et al. (1995) and Sato et al. (1993) respectively, as presented in the IPCC TAR (see Figures 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 over the future time periods examined here have been assumed constant at levels equivalent to the scaled mean forcings over the past 22 and 100 years respectively. In other words, we have assumed a scaled solar forcing of $+0.44$ and $-0.14\ \mathrm{W/m^2}$ for volcanic forcing, which is together $0.67\ \mathrm{W/m^2}$ above the natural forcing of the 1861–1890 period.[13]

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 to the above solar and volcanic forcing assumptions 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 separating 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 7AEM runs (see Tables I–III). Thus, it should be noted that the presented overshooting risks (Figure 8) 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 (Sections 4.1 to 4.4). 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, the associated radiative forcing would rise markedly in the future. By inverting Equation (1) the total radiative forcing can be expressed in equivalent CO_2 concentrations – the CO_2 concentration which would produce that level of radiative forcing if acting alone. In CO_2 equivalent terms the radiative forcing would rise to 527 ppm CO_2eq by 2100 and 899 ppm CO_2eq by 2400 (excl. natural forcing). For comparison the actual CO_2 concentration would rise up to 531 ppm by 2100 and

929 ppm by 2400. The relatively small difference between CO_2 and CO_2eq is due to the offsetting effects of aerosol. A central estimate is that at the global mean level the direct and indirect aerosol cooling effects are sufficient to approximately counteract the warming effects of the non-CO_2 well mixed greenhouse gases. Temperature would increase monotonically up to 4.2 °C in 2400 (2.0 °C in 2100) – according to the 7AEM results. Assuming lower (1.5 °C) and higher (4.5 °C) climate sensitivities, the temperature range in 2400 spans from 2.5 to 6.1 °C, respectively (2100: 1.4 to 2.7 °C).[14] The 90% confidence ranges for global mean temperatures based on climate sensitivity estimates by Murphy et al. (2004) is 1.9 to 3.0 °C in 2100 and 3.7 to 7.0 °C by 2400. See Table I for further estimates for different climate sensitivity PDFs.

Figure 4 presents an example of a probabilistic assessment of warming resulting from constant emissions. In this figure the 1, 10, 33, 66, 90 and 99% percentiles for warming estimates are shown based on the IPCC range of climate sensitivity as codified by Wigley and Raper (2001).

TABLE I

'Constant emission' warming commitment: temperature implications in the case where emissions are held constant at today's (2005) levels

	Temperature above pre-industrial (°C above pre-industrial)							
Climate sensitivity	2000	2005	2050	2100	2200	2400	EQUI w NF	EQUI w/o NF
7 AOGCM ensemble mean								
∼2.8	0.7	0.8	1.5	2.0	2.9	4.2	5.2	4.9
Wigley								
5%: 1.50	0.5	0.6	1.0	1.4	1.8	2.5	2.7	2.6
50%: 2.60	0.6	0.8	1.4	2.0	2.8	4.0	4.8	4.5
95%: 4.50	0.7	0.9	1.9	2.7	4.1	6.1	8.5	7.9
Murphy								
5%: 2.40	0.6	0.7	1.4	1.9	2.6	3.7	4.4	4.1
50%: 3.42	0.7	0.8	1.7	2.3	3.4	5.0	6.4	6.0
95%: 5.37	0.8	0.9	2.0	3.0	4.6	7.0	10.2	9.5
Knutti								
5%: 1.47	0.5	0.6	1.0	1.3	1.8	2.5	2.7	2.5
50%: 4.33	0.7	0.9	1.9	2.7	4.0	6.0	8.1	7.6
95%: 9.28	0.9	1.1	2.5	3.9	6.2	>8	18.1	17.0

Note. Results are given for the 7AEM as well as the probabilistic calculations based on different estimates of climate sensitivity PDFs by Wigley and Raper (2001), Murphy et al. (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).

TABLE II
'Present forcing' warming commitment: temperature implications in case that radiative forcing is held constant at today's (2005) levels. Otherwise as Table I

	Temperature above pre-industrial (°C above pre-industrial)							
Climate Sensitivity	2000	2005	2050	2100	2200	2400	EQUI w NF	EQUI w/o NF
7 AOGCM ensemble mean								
~2.8	0.7	0.8	1.0	1.1	1.1	1.2	1.5	1.2
Wigley								
5%: 1.50	0.5	0.6	0.7	0.7	0.8	0.8	0.8	0.6
50%: 2.60	0.6	0.7	0.9	1.0	1.1	1.1	1.4	1.1
95%: 4.50	0.7	0.9	1.2	1.4	1.5	1.7	2.4	1.9
Murphy								
5%: 2.40	0.6	0.7	0.9	1.0	1.0	1.1	1.3	1.0
50%: 3.42	0.7	0.8	1.1	1.2	1.3	1.4	1.8	1.4
95%: 5.37	0.8	0.9	1.3	1.5	1.7	1.9	2.9	2.2
Knutti								
5%: 1.47	0.5	0.6	0.7	0.7	0.8	0.8	0.8	0.6
50%: 4.33	0.7	0.9	1.2	1.3	1.5	1.7	2.3	1.8
95%: 9.28	0.9	1.1	1.7	2.0	2.3	2.8	5.0	3.9

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

	Temperature above pre-industrial (°C above pre-industrial)							
Climate Sensitivity	2000	2005	2050	2100	2200	2400	EQUI w NF	EQUI w/o NF
7 AOGCM ensemble mean								
~2.8	0.7	0.8	0.9	0.7	0.6	0.4	0.4	0.1
Wigley								
5%: 1.50	0.5	0.7	0.6	0.5	0.4	0.3	0.2	0.0
50%: 2.60	0.6	0.8	0.8	0.7	0.5	0.3	0.4	0.1
95%: 4.50	0.7	1.0	1.2	1.0	0.7	0.5	0.7	0.1
Murphy								
5%: 2.40	0.6	0.8	0.8	0.7	0.5	0.3	0.3	0.1
50%: 3.42	0.7	0.9	1.0	0.8	0.6	0.4	0.5	0.1
95%: 5.37	0.8	1.0	1.3	1.1	0.8	0.6	0.8	0.2
Knutti								
5%: 1.47	0.5	0.7	0.6	0.5	0.4	0.3	0.2	0.0
50%: 4.33	0.7	1.0	1.1	0.9	0.7	0.5	0.6	0.1
95%: 9.28	0.9	1.2	1.6	1.5	1.2	0.9	1.5	0.4

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

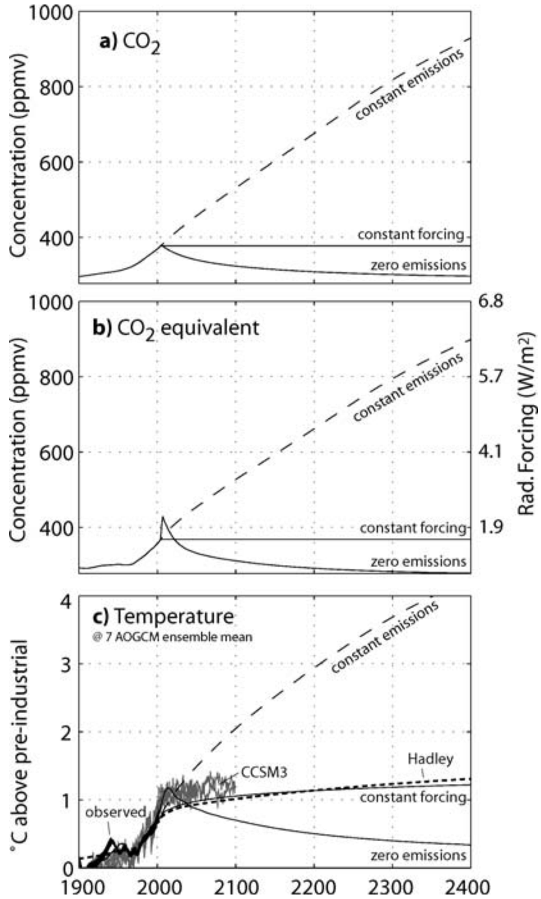

Figure 3. Effects of abrupt cessation of emissions, constant radiative forcing, and constant emissions from 2005 onwards (a) CO_2 concentrations, (b) CO_2 equivalent concentrations and radiative forcing, (c) global mean surface temperature. Shown are results of the '7 AOGCMs ensemble mean' runs with an approximate climate sensitivity of 2.8 °C. In addition, the 20th warming commitment results are plotted for the CCSM3 model runs (Meehl et al., 2005) (grey solid lines). The Hadley centre's estimate of the warming commitment related to a constant radiative forcing (dotted grey line in panel c) (Hadley Centre, 2002) is approximately equivalent to the 7AEM one derived here. All temperature model runs are calibrated towards the 1961–1990 observational record data from (Folland et al., 2001), shown with uncertainties (grey band with black solid line).

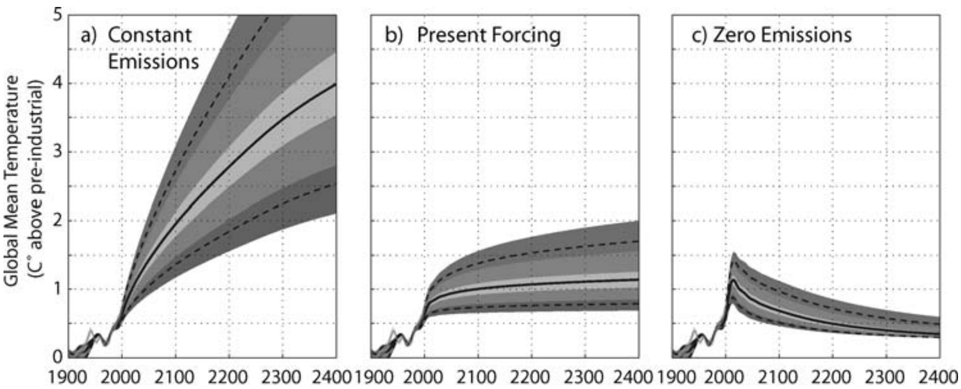

Figure 4. Global mean temperature increase in case that emissions are held constant at 2005 levels (left a), that radiative forcing is held constant (middle b) or that emissions are abruptly reduced to zero (right c). Likelihood ranges are given for the lognormal fit to the conventional 1.5–4.5 °C IPCC 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).

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). Other models yield similar estimates when holding radiative forcing constant (Meehl et al., 2005; Wigley, 2005). Using a climate model with higher sensitivity (3.7 °C) than in the Hadley Centre analysis, the results of Wetherald et al. (2001)[15] indicate a total warming at equilibrium of around 2.1 °C above 1861–1890 would occur with forcing held constant at year 2000 levels.[16]

In this study, results suggest an increase of global mean surface temperatures by about 0.4 °C up to 2400 over the observed 2002 levels (1.2 °C above pre-industrial), if radiative forcing were held fixed at present levels (estimated to be 1.93 W/m^2 including natural forcings in 2005) (7AEM). 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 and 4.5 °C), the 2400 total warming lies between 0.8 and 1.7 °C. 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 7AEM, if it is assumed that SO_2 aerosol emissions were to cease, but greenhouse gas concentrations remain at the current level (452 ppm CO_2 equivalence).[17]

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. 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 3c). Until 2100 it seems likely that temperature levels at least as high as year 2000 levels would prevail, even if all human-induced emissions were to be 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 (in the absence of negative emissions).[18] The indicated lower bound of approximately 0.3 to 0.4 °C results largely from the increase in solar forcing since pre-industrial times and assumed continuation of current levels (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 300 ppm (see Figure 3a). 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 order to see how the geophysical warming commitment increases with time, we show the effects of emissions being switched off at six ten-year intervals from 2001 to 2051 for the SRES A1B scenario on global mean 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 (see Table IV and Figure 5). This estimate is similar to that made by Ramanathan (1988) of

TABLE IV
The geophysical warming commitment over time (columns) is depending on the year, when emissions are reduced to zero (rows)

	Temperature above pre-industrial (°C above pre-industrial)							
Ceasing emissions	2000	2005	2050	2100	2200	2400	EQUI w NF	EQUI w/o NF
2001	0.7	1.1	0.8	0.7	0.5	0.3	0.4	0.0
2011	0.7	0.7	1.0	0.8	0.6	0.4	0.5	0.1
2021	0.7	0.7	1.3	1.0	0.8	0.6	0.6	0.3
2031	0.7	0.7	1.7	1.3	1.0	0.7	0.8	0.4
2041	0.7	0.7	2.1	1.6	1.2	0.9	0.9	0.6
2051	0.7	0.7	2.2	1.9	1.4	1.1	1.1	0.8

Note. 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).

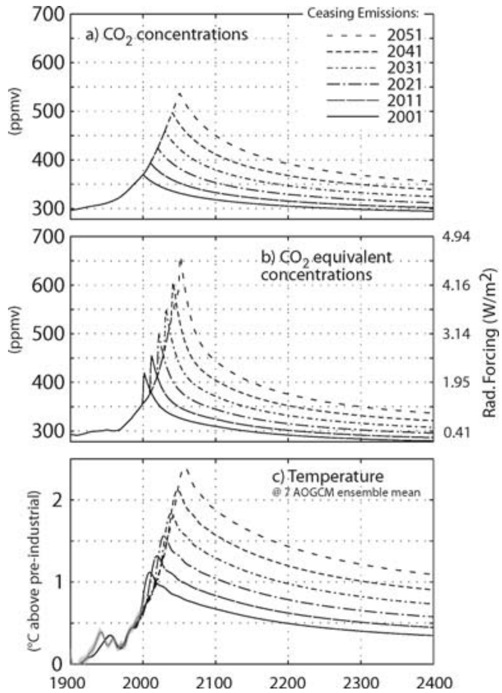

Figure 5. Effects of 10 year lags in reducing emissions to zero on (a) CO_2 concentrations, (b) CO_2 equivalent concentrations and radiative forcing, (c) global mean temperature. Emissions are reduced to zero in 2001, 2011,. . ., 2051 after following the SRES A1B-AIM scenario.

0.15–0.5 °C warming commitment for each decade of continued growth in greenhouse gas emissions.

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 7AEM 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 450 ppm CO_2 scenarios result in a warming in the range of 2.2–2.4 °C above pre-industrial levels (7AEM). 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 400 ppm scenarios the range is 1.9–2.1 °C in 2100. The 350 ppm CO_2 stabilization scenarios of Azar et al. (in press) yield a warming of about 1.5–1.7 °C by 2100.[19] In contrast, temperatures in 2100 will increase to levels that are between 2.5 to 4.8 °C above pre-industrial ones, if

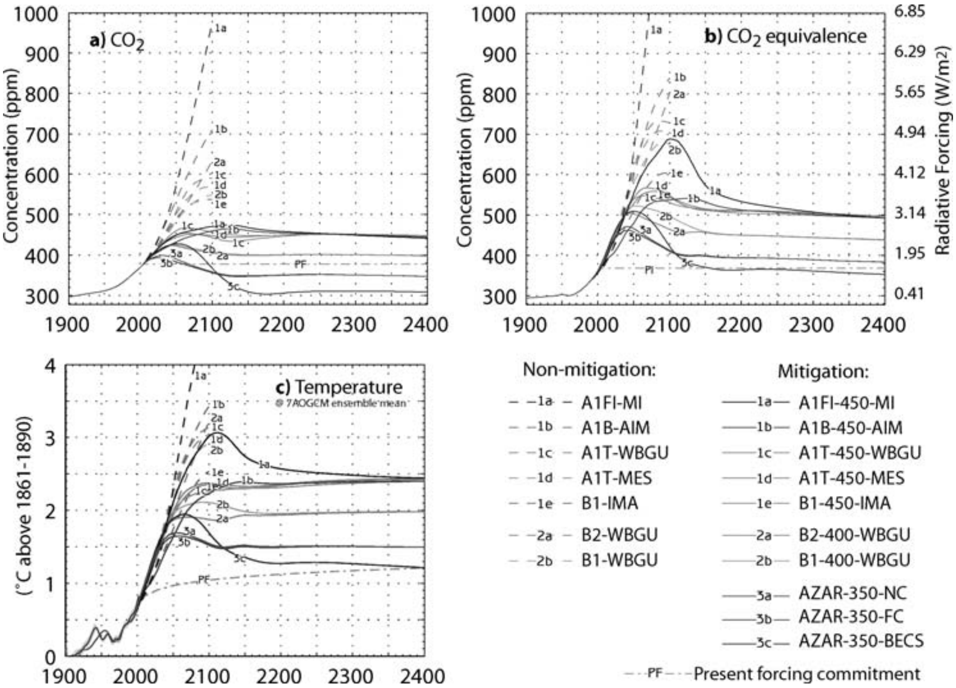

Figure 6. The climatic effects of a range of SRES non-mitigation scenarios (dotted line) and 350–450 ppm CO_2 stabilization scenarios (solid lines) on (a) CO_2 concentrations, (b) CO_2 equivalent concentration and radiative forcing, (c) global mean. For comparison, the 'constant present forcing' run is plotted as in Figure 3.

emissions were to follow one of the non-mitigation scenarios analysed here (see Figure 6).

In summary, if the 350 and 400 ppm CO_2 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 2002 (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 400 ppm. 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., in press).[20] 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

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 three climate sensitivity PDF estimates by 'Wigley' et al., 'Murphy' 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 400 ppm, overshooting 2 °C in equilibrium is 'unlikely' (risk below 33%) for two out of the three 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**
	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**
	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**
	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**
	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**
	Knutti	86	**10**	**0**	52	38	**18**	**0**

will stabilize at about 310 ppm and CO_2 equivalent concentrations at about 350 ppm by 2150 (see Table V).

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

The risk of overshooting 2 °C is about 66% for the 450 CO_2 scenarios (≈500 CO_2eq) (Figure 7a), approximately 33% for the 400 ppm CO_2 scenarios (≈440 ppm CO_2eq) (Figure 7b), and 33% around the peak and 2% in the long-term for the analysed 310 ppm CO_2 scenario AZAR-350-BECS (≈350 ppm CO_2eq) (Figure 7c; cf. Table V for risks in equilibrium without natural forcing).

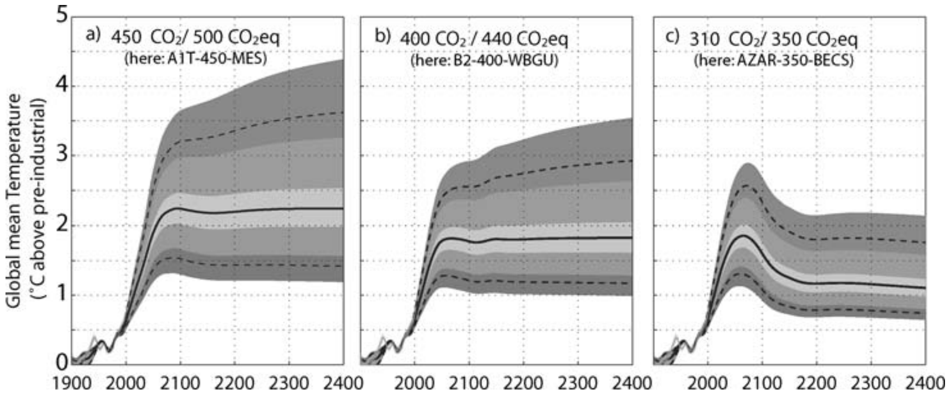

Figure 7. Temperature increase for mitigation scenarios stabilizing CO_2 at 450 ppm (left a), 400 ppm (middle b) and 310 ppm CO_2 (right c). The CO_2 equivalent concentrations in 2400 are about 500, 440 and 350 ppm, respectively (cf. Figure 6). Otherwise as Figure 4: The underlying climate sensitivity PDF is based on the conventional 1.5 to 4.5 °C range (Wigley and Raper, 2001).

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 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 6c). 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 not taken into account for these equilibrium calculations (see Section 3.5).

Given contemporary policy discussions around warming limits of 2 °C (European Community, 1996; Caldeira et al., 2003)[1] we focus here on the probability that committed warming will lie above 2 °C for different long term stabilization levels. 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 stay within the 2 °C limit for the lower concentration levels. In contrast, the Forest et al. (2002) 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

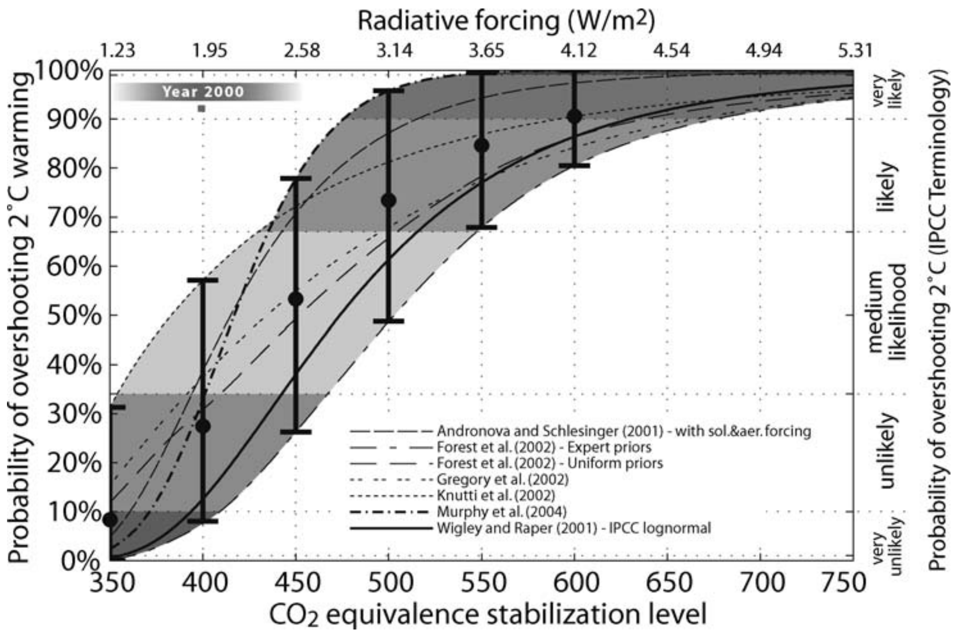

Figure 8. Risk of overshooting a 2 °C target. Current estimates of the climate sensitivity suggest that only by stabilizing anthropogenic radiative forcing at levels below 400 or 450 ppm CO_2 equivalent concentrations, the risk of overshooting the 2 °C target can be termed "unlikely". The actual 2000 forcing range and its uncertainty (upper left bar) is taken from Knutti et al. (2002), with the grey square indicating this study's present (2005) forcing assumption.

the "unlikely" range around 475 ppm CO_2 equivalent stabilization level and is further reduced to "very unlikely" below the 410 ppm CO_2 equivalent stabilization level.[21]

For stabilization of greenhouse gas concentrations at 550 ppm CO_2 equivalent, (corresponding approximately to a 475 ppm 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.[22] 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 450 ppm CO_2 equivalent then the risk of exceeding 2 °C would be lower, but still significant, in the range of 26 to 78% (mean 47%). This could roughly be categorized as having a "medium likelihood". The 450 ppm CO_2eq stabilization level would correspond roughly to the 400 ppm CO_2 scenarios discussed above. Only for stabilization levels of 400 ppm 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 350 ppm 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 the long-term. 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%. 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 500 ppm CO_2 equivalent or rather a 350 ppm 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).

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. 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 400 ppm 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 that corresponds to forcing differences in a specific year (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 7AEM climate simulations (see Figure 9). The benefits increase to a range of 0.13–0.60 °C for higher climate sensitivity (4.5 °C) and decrease to a range of 0.10–0.33 °C for lower sensitivity (1.5 °C). Note that for the B1 IMAGE scenarios the 450 ppm CO_2 scenario is *warmer* than the reference case by about 0.2 °C in 2050, which is due to the reductions of sulphur emissions in the 450 ppm CO_2 scenario (see Figure 9).

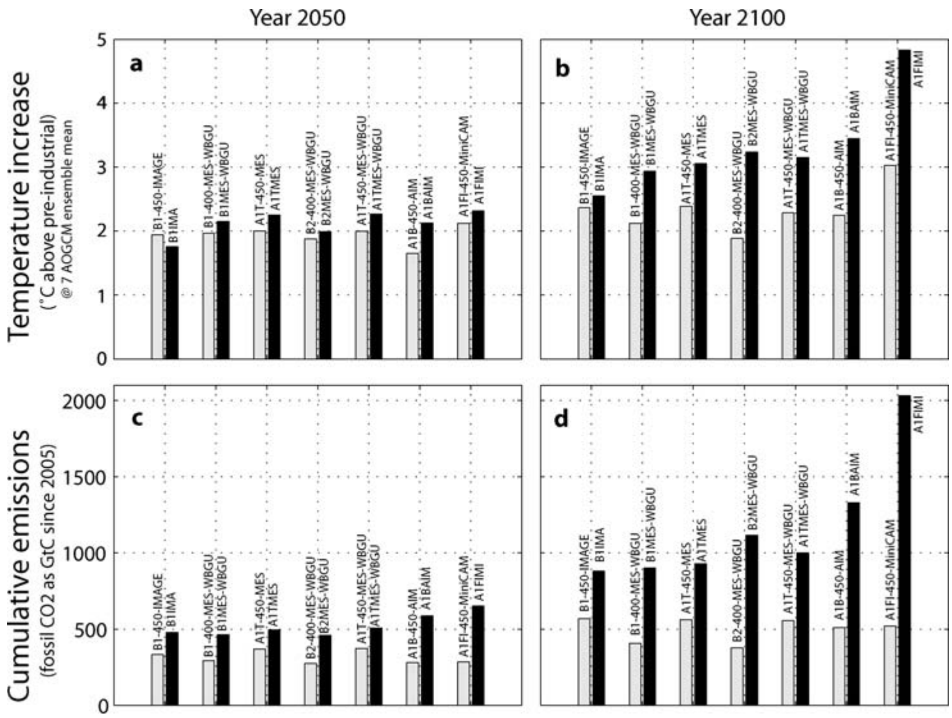

Figure 9. Comparison of cumulative emissions and temperature increase for 2050 and 2100. The non-mitigation scenarios (black bars) have higher cumulative emissions (c,d) than the mitigation scenarios (grey bars). Consequently, the 'current' temperature increase up to year 2050 and 2100 is lower for almost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

It can be seen that the further one goes 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 7AEM 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)). Statistical analysis of existing multi-gas mitigation and non-mitigation scenarios suggests the following regression relationship for a climate sensitivity of about 2.8 °C ('7AEM'):

$$\Delta T_{\mathrm{current},t} = \frac{0.16\,^{\circ}\mathrm{C}}{100\,\mathrm{GtC}} * \sum_{i=2000}^{t} \Delta E_i \tag{3}$$

with ΔE_i: Difference in fossil CO_2 emissions in year i between the unmitigated and mitigated cases as index of the (multi-gas) mitigation effort.

$\Delta T_{\mathrm{current},t}$: Difference in temperature in year t. between the unmitigated and mitigated cases.

As in the case of Equation (4), the regression coefficients are estimated from warming and cumulative emission differences between the non-intervention and

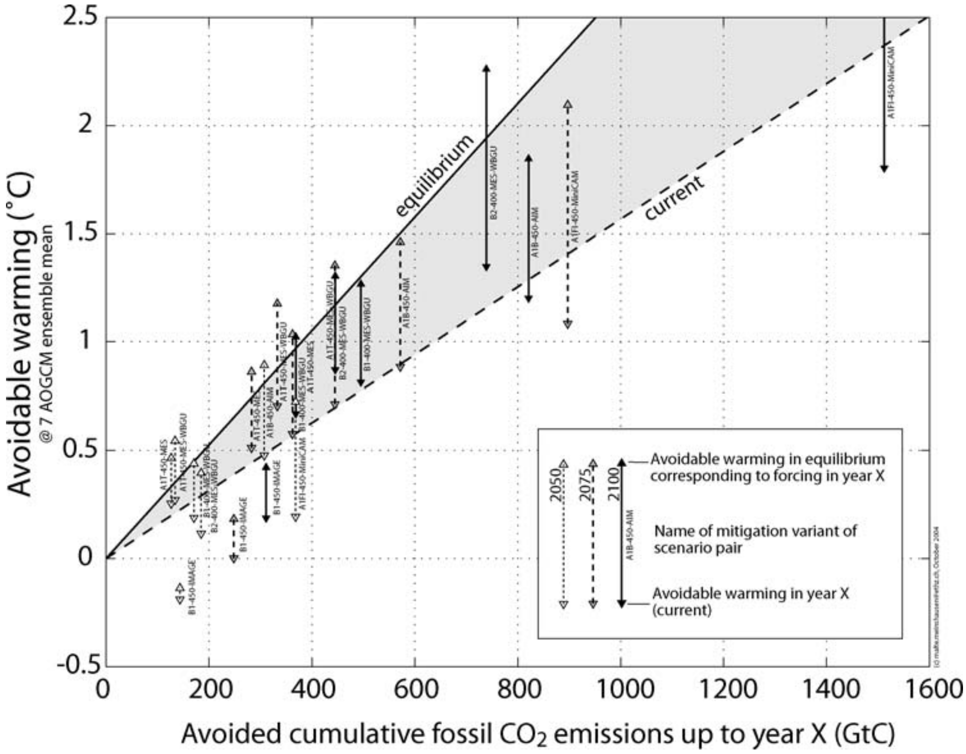

Figure 10. Benefits of mitigation. Here paired comparisons between mitigation and non-mitigation scenarios of the same SRES scenario families are shown. The horizontal axis displays the mitigation effort in terms of the difference in cumulative fossil CO_2 emissions of a mitigation and non-mitigation 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.

intervention scenario variants in 2050, 2075, and 2100 (see Figure 10). A higher or lower climate sensitivity would produce a higher or lower temperature scaling factor in Equations (3) and (4).[23]

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 fossil CO_2 emissions avoided up to specific year t, 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 of mitigation. The equilibrium benefits are computed as the difference of equilibrium warming that correspond to the forcing of the mitigation and non-mitigation scenario in a specific year. The avoided emission are the integral of the difference between the unmitigated and mitigated emissions scenarios from the base year until a specific year t of interest. A linear least squares regression across the scenario pairs for the years 2050, 2075 and 2100 suggests that 0.26 °C warming can be avoided in equilibrium for every 100 GtC of avoided fossil CO_2 emissions ('7AEM'):

$$\Delta T_{\text{equilibrium},t} = \frac{0.26\,^{\circ}\mathrm{C}}{100\,\mathrm{GtC}} * \sum_{i=2000}^{t} \Delta E_i \tag{4}$$

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

$\Delta T_{\text{equilibrium},t}$: Difference of equilibrium temperatures that correspond to radiative forcing levels in year t.

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 warming that we are committed to – taking into account climate system as well as socio-economic inertia.

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 350 ppm 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 potentially be accelerated compared to the rates deployed in the 350 ppmv CO_2 scenarios if there were sufficient political interest in doing so.

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. 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.[24]

Furthermore, increased mitigation efforts and hence lower concentrations than analysed here might become more plausible if scientific developments raise and broaden the perceived risk of large scale climate system alterations. 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 m 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 (Stocker and Wright, 1991; Rahmstorf, 1995, 1996), 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 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 a stabilization of radiative forcing at around 400 ppm CO_2 ($\sim$2 W/m^2) equivalence is needed, if global long-term temperature change is to be limited to at or below 2 °C with reasonable certainty. In 2000, the radiative forcing due to the well mixed greenhouse gases was already equivalent to 440 $\pm$ 20 ppm CO_2 (2.43 $\pm$ 0.24 W/m^2) (Ramaswamy et al., 2001, Table 6.11). The 2000 net radiative forcing was likely to be lower, equivalent to 350 to 450 ppm CO_2 (1.25–2.5 W/m^2 – cf. Knutti et al. (2002)), with positive contributions due to changes in tropospheric ozone and solar forcing, and (dominant) negative contributions due to (uncertain) aerosol cooling, among others. Thus, radiative forcing levels are likely to (or might have already) temporarily overshoot the levels that would be required to limit the temperature increase above preindustrial to below 2 °C in the long-term (see Figure 8). This does however not mean, that 2 °C warming is inevitable. Continued emission reductions might reduce the radiative forcing levels again in the long-term, so that the equilibrium warming levels might not be felt thanks to the inertia of the climate system.

The lower mitigation scenarios used here overshoot their ultimate CO_2 equivalent stabilization levels in the 21st century. The results suggest that if the ultimate stabilization level is below 450 ppm 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 the sense that the lower the peak level, the faster would need to be the emission reductions.

In any case, it becomes clear that rapid emission reductions are needed within the next few decades globally in order to substantially limit the risk of overshooting the European Union's 2 °C goal[1]. Only scenarios that aim at stabilization levels at or below 400 ppm CO_2 equivalence (~350 ppm CO_2) can limit the probability of exceeding 2 °C to reasonable levels (see Table V).

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 to 4.5 °C IPCC uncertainty range has been applied here (Wigley and Raper, 2002) (cf. Table V)

Mitigation scenario	Risk > 2 °C in equilibrium (Wigley)	Risk > 2 °C ~2100 (Wigley)	Global emissions relative to 1990 (%)					
			All GHGs			Fossil CO_2 only		
			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%

For moderate levels of risk and for scenarios using a conventional technological mix including renewables and some carbon capture and storage global fossil CO_2 emissions need to be limited to around a 20% increase by 2020 relative to 1990 and then decrease to around 40–60% below 1990 levels by 2050 (see Table VI).

5.4. INTERACTION BETWEEN AEROSOL AND WARMING COMMITMENT TIMESCALE

The committed warming, or level of warming that is avoidable, also depends on the residence times of the atmospheric radiative forcing agents. Tropospheric Aerosols have a short atmospheric residence time (days to weeks). Reductions in aerosols (which overall are estimated to 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 on shorter times scales than apply to the well mixed greenhouse gases. 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 Figures 3 and 10 and cf. Wigley, 1991). Hence the avoidable warming in the short term may not be as great as sometimes assumed. The robustness of these results outlined here need 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 from the mitigation scenarios used in this work arising from the sulphur emission reductions in these scenarios 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, actual reactive gas emissions, which lead to tropospheric ozone formation that adds positively to radiative forcing may as well be less than assumed under the post-SRES and SRES scenarios, 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 9).

5.5. UNCERTAINTY IN CLIMATE SENSITIVITY

The climate sensitivity strongly affects estimates of the warming to which we are committed. Firstly, the higher the sensitivity, the higher is the equilibrium 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). 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 climate sensitivity estimates in Figure 2 there is a large uncertainty in this key parameter, which is of quite fundamental significance for policy in general and specifically in relation to the question of long term warming commitments. This would be substantially reduced if there were some fundamental narrowing of the uncertainty range such as the the ruling out of climate sensitivities higher than 4 °C and lower than 1.5 °C, as has been argued by Schneider von Deimling et al. (2004) on the basis of assessment of constraints on climate system feedbacks that applied during the last the Last Glacial Maximum (about 21 000 years ago) and projected to a doubled CO_2 climate. However, several factors weigh against a strong conclusion based in this or earlier paleoestimates of climate sensitivity (Lorius et al., 1990; Hoffert and Covey, 1992; Covey et al., 1996; Alley, 2003). It cannot be assumed that the scale of climate system feedbacks during glacial times will be limited in the same way in a warmer world in the future. Much remains to be explained in relation to the operation of the hydrological cycle and oceans for example during warmer period of earth system history such as the Paleo Eocene Thermal Maximum (Schmidt and Shindell, 2003; Renssen et al., 2004) which may be relevant to the future.

Whilst research will assist in narrowing uncertainties, policy action based on current scientific knowledge may need to rely on a precautionary approach as recognised in Article 3.3 of the UNFCCC.

5.6. CARBON CYCLE FEEDBACKS AND THE WARMING COMMITMENT FOR A PARTICULAR EMISSION SCENARIO

Positive terrestrial carbon cycle feedbacks (Jones et al., 2003a,b) or releases of methane hydrates (Archer and Buffett, 2005) would add to the warming arising from any particular emission scenario as they would increase CO_2 and methane levels in the atmosphere substantially above the levels assumed in the current work. This would result in larger long term warming for any given emission scenario used here.

5.7. 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 is likely to respond faster to a reduction in forcing than to an increase, due to the physics of the ocean response to forcing changes (Stouffer, 2004). 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. 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. Thus, the rate of cooling for the geophysical warming commitment and the lower mitigation scenarios might actually be faster than presented here (see Figures 3, 5 and 6).

5.8. 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 and reactions with igneous rocks on land so that after 100 000 years about 7% of present emissions would still remain in the atmosphere (Archer et al., 1997, 1998; Archer, 2005). This implies a significant future commitment arising from contemporary emissions patterns over millennial time scales even if all emission ceased, unless there is substantial use of technologies such as the combined biomass burning and CO_2 capture and storage option – assuming the containment efficiency of the captured CO_2 is high for very long periods (Haugan and Joos, 2004) For example, in the absence of the latter option, 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.[25]

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 temperature characteristic of the mid 20th century by the end of the 22nd century, namely to 0.3–0.5 °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).

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., in press) 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 '7AEM'. On the other hand, if one believes that the maximum plausible policy effort corresponds to the B2 WBGU 400 ppm 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 450 ppm 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 to 4.5 °C) suggests that only by stabilizing anthropogenic radiative forcings at levels below CO_2 equivalent concentrations of 440 ppm (CO_2 only below 400 ppm) is there more than a 66% chance of limiting the global mean temperature increase to below 2 °C. Five out of the 6 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 400 ppm CO_2eq in equilibrium (see Figure 8).

The scenario range above does not necessarily cover the full range of possibilities. For example the introduction of biomass fuel with carbon capture and storage technology used in the Azar et al. (in press) 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 damages were identified for warming levels whose avoidance or prevention, pursuant to international legal obligations under Article 2 of the UNFCCC, required that greenhouse gas concentrations be reduced after peaking. Whilst there is no global 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. Examples of potential thresholds in this area include the risk of substantial ecosystem damage which has led to a finding that "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) and the risk of West Antarctic Ice Sheet disintegration or collapse triggered by either atmospheric or ocean warming (Oppenheimer and Alley, 2004). The results of this work suggest that if operationalization of Article 2 of the UNFCCC required that global mean surface warming be limited below 2 °C with a high (90% or greater probability) then in the 22nd century CO_2 levels would need to be drawn down to below 350 ppmv CO_2 equivalent.

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 '7AEM' computations, the avoidable warming in a given year is found to be about 0.16 °C for every 100 GtC 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 100 GtC fossil CO_2 emissions in equilibrium.

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Notes

[1]The Presidency Conclusion of the European Council of 22 and 23 March 2005 state in paragraph 43 "The European Council acknowledges that climate change is likely to have major negative global environmental, economic and social implications. It confirms that, with a view to achieving the ultimate objective of the UN Framework Convention on Climate Change, the global annual mean surface temperature increase should not exceed 2 °C above pre-industrial levels." This decision adds weight to the position first adopted by the Council of Enviroment Ministers of the European Union in 1996.

[2]The temperature anomaly of 2002 compared to 1861–1890 is based on data by Folland et al. (2001) including updates with 2001–2002 data. The uncertainty band of ±0.2 °C is taken from IPCC's 19th century warming estimate. An uncertainty analysis based on error estimates by Folland et al. suggests a slightly lower uncertainty band (2σ) of ±0.15 °C.

[3]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__11_data/Annual/land+sst__11_web.txt, accessed 15. October 2004.

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

[5]There are different conventions in the literature in regard to wether volcanic forcing is adjusted to have (1) a zero mean or (2) left as absolute (negative) perturbation. Consequently, it is an issue whether net present radiative forcing, including natural forcing, is specified as (a) difference between present and the negative pre-industrial forcing (average) or (b) the 'zero line'. Thus, it is not straightforward to

compare all 'present forcing' data, if the applied convention is not specified, as is often the case. This study assumed volcanic forcing as being negative at all times (2) and we report net radiative forcing here as the difference between present and earlier period's means (a): the net/human-induced/natural radiative forcing for 2005 relative to the periods 1861–1890 and 1770–1800 is 1.93/1.26/0.67 and 2.03/1.48/0.54 W/m^2, respectively. The human-induced forcing for 2005 above 1765 is 1.50 W/m^2. For natural forcing assumptions, see as well Section 3.5.

[6]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.

[7]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.

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

[9]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.

[10]The projection range for the 'present forcing' warming commitment due to the 1.5 to 4.5 °C uncertainty range in climate sensitivity narrows slightly, if a conventional uncertainty range for ocean mixing (1.3 to 4.1 cm^2/s, Wigley, 2005) is assumed to be dependent on climate sensitivity. The sensitivity of the simple climate model results to uncertainties in ocean mixing is highest for the near-term transient climate response and ceases in the long-term equilibrium. Specifically, the uncertainty range narrows in 2050 and 2400 by 18 and 1%, respectively, if the 1.3 (4.1) cm^2/s ocean mixing rate is assumed to go hand in hand with a 1.5 (4.5)°C climate sensitivity in comparison to computing future temperatures by using a medium range 2.3 cm^2/s ocean mixing ratio independent of climate sensitivity. This is generally in line with results by Wigley, who estimated that the effect of ocean mixing uncertainties being relatively small compared to uncertainties of climate sensitivity and present forcing (Wigley, 2005).

[11]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.

[12]Note, that the conventionally cited 'combined pdf' from Andronova & Schlesinger (Andronova and Schlesinger, 2001) has been combined from PDF estimates of which some do not take into account aerosol forcing or variations in solar radiation.

[13]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. Note as well endnote 5.

[14]Note that there are corresponding slight variations in CO_2 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), CO_2 concentration in 2400 will be 900 (960) ppm.

[15]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.

[16]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).

[17]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 7AEM procedure.

[18]In regard to negative emissions: One potential technique for increasing the rate of CO_2 removal from the atmosphere beyond its natural limits could be biomass burning with subsequent capture and storage of CO_2 in the flue gas (Azar et al., in press).

[19]As aforementioned (Section 2.4), the non-CO_2 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-CO_2 emission reductions were assumed below the ones of the WBGU B2-400 scenario.

[20]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., in press).

[21]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%).

[22]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.

[23]Note that the regression factor (0.16 °C/100 GtC) 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 from the regression as they fall far outside the range of the other scenarios and would thereby overproportionally influence the regression. Including the A1FI-MiniCAM scenario in the regression leads to factors of 0.14 °C/100 GtC and 0.23 °C/100 GtC for current and equilibrium avoided warming, respectively.

[24]In the post SRES scenarios, including the WBGU variants, the non-CO_2 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.

[25]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) CO_2 did not exceed 280–290 ppm throughout the last 420 000 years.

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