IOP Publishing — Environmental Research Letters

Environ. Res. Lett. **2** (2007) 014001 (10pp) doi:10.1088/1748-9326/2/1/014001

Allowable CO_2 concentrations under the United Nations Framework Convention on Climate Change as a function of the climate sensitivity probability distribution function

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Received 6 July 2006
Accepted for publication 2 February 2007
Published 16 February 2007
Online at stacks.iop.org/ERL/2/014001

Abstract
Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC) calls for stabilization of greenhouse gas (GHG) concentrations at levels that prevent dangerous anthropogenic interference (DAI) in the climate system. Until recently, the consensus viewpoint was that the climate sensitivity (the global mean equilibrium warming for a doubling of atmospheric CO_2 concentration) was 'likely' to fall between 1.5 and 4.5 K. However, a number of recent studies have generated probability distribution functions (pdfs) for climate sensitivity with the 95th percentile of the expected climate sensitivity as large as 10 K, while some studies suggest that the climate sensitivity is likely to fall in the lower half of the long-standing 1.5–4.5 K range. This paper examines the allowable CO_2 concentration as a function of the 95th percentile of the climate sensitivity pdf (ranging from 2 to 8 K) and for the following additional assumptions: (i) the 50th percentile for the pdf of the minimum sustained global mean warming that causes unacceptable harm equal to 1.5 or 2.5 K; and (ii) 1%, 5% or 10% allowable risks of unacceptable harm. For a 1% risk tolerance and the more stringent harm-threshold pdf, the allowable CO_2 concentration ranges from 323 to 268 ppmv as the 95th percentile of the climate sensitivity pdf increases from 2 to 8 K, while for a 10% risk tolerance and the less stringent harm-threshold pdf, the allowable CO_2 concentration ranges from 531 to 305 ppmv. In both cases it is assumed that non-CO_2 GHG radiative forcing can be reduced to half of its present value, otherwise; the allowable CO_2 concentration is even smaller. Accounting for the fact that the CO_2 concentration will gradually fall if emissions are reduced to zero, and that peak realized warming will then be less than the peak equilibrium warming (related to peak radiative forcing) allows the CO_2 concentration to peak at 10–40 ppmv higher than the limiting values given above for a climate sensitivity 95th percentile at 4.5 K. Even allowing for the difference between peak realized and peak equilibrium warming, and assuming that present non-CO_2 GHG forcing can be cut in half, a CO_2 concentration of 410 ppmv or less constitutes DAI for every combination of harm-threshold pdf and risk tolerance considered here if the 95th percentile of the climate sensitivity pdf is 4.5 K or greater.

Keywords: global warming, climatic change, United Nations Framework Convention on Climate Change, greenhouse gases

1. Introduction

Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC) calls for the stabilization of atmospheric greenhouse gas (GHG) concentrations at levels that 'prevent dangerous anthropogenic interference with the climate system'. An increase in carbon dioxide (the single most important anthropogenic GHG) constitutes interference in the climate system through changes in ocean chemistry (ultimately affecting the marine component of the carbon and sulfur cycles) and through the trapping of infrared radiation, which leads to a warming of the climate and ultimately to a variety of impacts. The global mean warming for a benchmark CO_2 doubling is referred to as the *climate sensitivity*. 'Dangerous anthropogenic interference' (DAI) involves GHG concentrations that have some unacceptably large probability of causing a change in climate large enough to have some non-negligible probability of provoking unacceptably large negative impacts. Thus, the determination of the GHG concentrations that constitute DAI depends on (i) the probability distribution function (pdf) of climate sensitivity, (ii) the pdf for the minimum sustained global mean warming that causes unacceptable harm, and (iii) the maximum probability of causing unacceptable harm that the global community is prepared to accept. Cultural factors and individual values enter into the determination of DAI in two ways: in determining the magnitude or kinds of harm that are acceptable or unacceptable, and in determining the maximum probability of exceeding these harm thresholds that will be accepted. Tolerable probabilities of harm depend in part on the cost of reducing the risk.

The trapping of infrared radiation due to an increase in GHG concentrations, prior to any response of the climate system except for adjustment of stratospheric temperatures, is referred to as *radiative forcing* (for an explanation of this definition see Harvey (2000), chapter 3). To within about 10% error, it is the total radiative forcing rather than the specific combination of GHGs that matters for climate. Thus, calling for stabilization of GHG concentrations is equivalent to calling for stabilization of total GHG radiative forcing. The increase in CO_2 concentration that is permitted under a given ceiling for total radiative forcing depends on the total radiative forcing by non-CO_2 GHGs. Aerosols such as sulfate and nitrate (associated with acid rain) have a negative forcing and so, if included in the total radiative forcing, would allow a greater radiative forcing by GHGs alone. However, emissions of aerosol precursors and the associated radiative forcing are expected to fall during the coming decades (Smith *et al* 2005) and, in any case, the climatic change associated with aerosols is not simply the negative of that associated with increasing GHGs, due to the fact that aerosols disproportionately reduce rainfall compared to their reduction in warming. Thus, aerosols cannot be used to increase the allowed GHG radiative forcing and hence the allowed CO_2 concentration.

Harvey (2007) has noted the importance of the distinction between DAI in the climate system and 'dangerous climatic change' (DCC). Much of the literature discussing Article 2 of the UNFCCC focuses on DCC rather than DAI, often using the two terms interchangeably as if they were the same thing (Caldeira *et al* 2003, Wigley 2004, Mastrandrea and Schneider 2004, Schneider and Mastrandrea 2005). DAI is a set of increases in GHG concentrations that have a non-negligible *possibility* of provoking a change in climate large enough that in turn has a non-negligible *possibility* of causing unacceptable harm to humans, human societies or natural ecosystems. DCC is a change of climate itself that has a non-negligible possibility of causing unacceptable harm to humans, human societies or natural ecosystems. In order to determine concentrations that constitute DAI, one needs to determine a plausible *upper limit* to the climate sensitivity, whereas to determine the GHG concentrations that will cause DCC, one needs to know the correct climate sensitivity. Inasmuch as there is considerable uncertainty concerning the correct climate sensitivity, the GHG concentrations that would cause DCC (and which therefore should be avoided, if the focus is on DCC) cannot be determined at present (and probably cannot be determined for several more decades). However, if the focus is on DAI, and if one can specify the maximum allowable risk of provoking unacceptable harm, then the maximum allowable GHG concentrations can be determined. If the radiative forcing by non-CO_2 GHGs is specified, then the maximum allowable CO_2 concentration can be determined. This exercise was carried out by Harvey (2007) for two different climate sensitivity pdfs and three different pdfs for the minimum sustained global mean warming that causes unacceptable harm. The allowable CO_2 concentrations obtained in Harvey (2007) pertain to sustained concentrations, such that the climate eventually comes into equilibrium with the elevated concentrations.

The purposes of this paper are to (i) show the systematic impact on the allowable long-term CO_2 concentration of a broader range of alternative pdfs for climate sensitivity than considered by Harvey (2007), given pdfs for the temperature change beyond which unacceptable harm occurs, various degrees of non-CO_2 GHG radiative forcing and various risk thresholds, and (ii) to assess the additional allowable CO_2 increase when account is taken of the fact that peak realized temperature (averaged over a specified number of years) can be less than the peak equilibrium temperature (that is, the temperature that would be in equilibrium with the peak radiative forcing) if emissions are reduced to zero (such that the CO_2 concentration declines after peaking).

2. Probability distribution functions for climate sensitivity and for the temperature threshold of unacceptable harm

From the mid 1970s until recently, the consensus viewpoint among climate scientists was that the climate sensitivity was likely to fall between 1.5 and 4.5 K, although the term 'likely' was never rigorously quantified. Recently, however, a number of studies have attempted to derive objective pdfs for climate sensitivity. The results are summarized in table 1 in terms of the 5th percentile of the pdf (the climate sensitivity such that there is thought to be only a 5% chance of the true sensitivity being smaller) and the 95th percentile (the climate

Table 1. Fifth and 95th percentiles from the pdf of climate sensitivity as determined by various workers. Wigley (2004) and Harvey (2007) assumed that the classical climate sensitivity range of 1.5–4.5 K represents a 90% probability, while other workers used various methods to generate a pdf.

Reference	5th–95th percentile range (K)
Wigley (2004), Harvey (2007)	1.5–4.5
Murphy *et al* (2004)	2.5–5.4
Hegerl *et al* (2006)	1.5–6.2
Piani *et al* (2005)	2.2–6.8
Knutti *et al* (2002)	1.7–8.6
Forest *et al* (2006)	2.1–8.9
Andronova and Schlesinger (2001)	1.0–9.3
Gregory *et al* (2002)	50th percentile at 6.1

Table 2. Parameters of the pdfs for climate sensitivity and for unacceptable temperature increases adopted here, and the corresponding median temperature change values.

95th percentile (K)	μ	σ	Median (K)
Standard climate sensitivity pdfs			
2	0.150	0.330	1.32
3	0.555	0.330	1.99
4	0.843	0.330	2.64
5	1.067	0.330	3.29
6	1.249	0.330	3.94
7	1.403	0.330	4.62
8	1.537	0.330	5.26
Alternative climate sensitivity pdfs			
4	0.788	0.364	2.56
5	0.955	0.398	3.04
6	1.081	0.432	3.46
7	1.186	0.466	3.86
8	1.207	0.530	4.06
Harm-threshold pdfs			
2.6	0.405	0.35	1.5
3.0	0.915	0.25	2.5

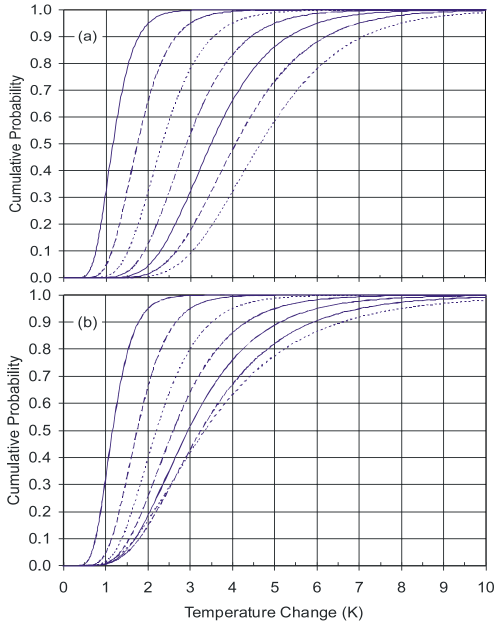

Figure 1. (a) Seven cumulative pdfs of climate sensitivity, chosen by varying μ with constant σ, so as to have 95th percentiles ranging from 2 to 8 K (in 1 K increments). (b) The first two pdfs from (a) along with five additional alternative climate sensitivity pdfs with 95th percentiles ranging from 4 to 8 K (in 1 K increments) with progressively larger σ.

sensitivity such that there is thought to be a 95% chance of the true sensitivity being smaller, or only a 5% chance of being larger). The 5–95% probabilities range from 2.4–5.4 K (Murphy *et al* 2004) to 1.0–9.3 K (Andronova and Schlesinger 2001). As explained in Frame *et al* (2005), the supposedly 'objective' pdfs depend in part on arbitrary prior assumptions, and as discussed in Harvey (2007), there are reasons for doubting those pdfs that generate non-negligible probabilities for climate sensitivities much greater than about 5 K.

However, here we will simply take the pdfs shown in table 1 as being equally plausible, and investigate the implications for allowable CO_2 concentrations of differing probabilities of very high sensitivity. For analytical convenience, we will generate eight different pdfs having 95th percentiles ranging from 2 to 8 K, rather than using the specific published pdfs. There is no evidence to support pdfs with a 95th percentile at 2–3 K, but they are included here simply to show how robust the final conclusions are. The pdfs are generated *here* using a log-normal distribution, as this allows for a long tail of high sensitivities but with low probability. The log-normal distribution depends on two parameters: the mean of the logarithm (μ) and the standard deviation of the logarithm (σ). Table 2 gives the values of μ and σ used for two sets of climate sensitivity pdfs: those shown in cumulative form in figure 1(a) (all with the same σ, so that the probabilities of low climate sensitivities fall sharply as the pdf is shifted to higher sensitivities by using larger μ) and those shown in figure 1(b) (in which σ increases as μ increases, so that μ does not have to increase as much and the probabilities of small climate sensitivities do not fall as rapidly with increasing 95th percentile). These shall be referred to as the standard and alternative sets, respectively.

With regard to the impacts of climatic change, there is no single change in global mean temperature beyond which large negative impacts occur. Rather, there will be an increasing number of increasingly negative impacts as greater climatic change occurs. Likely impacts of concern have been exhaustively reviewed by Warren (2006), while Harvey (2007) provides a more focused review of a few especially critical impact areas. Among the prominent impacts of concern and the likely global mean warming (relative to pre-industrial conditions) at which they would occur are the near-total loss of coral reef ecosystems with 1–2 K global mean warming, irreversible melting of the Greenland ice cap and destabilization of the West Antarctic Ice Sheet with 1–3 K global mean warming (and an eventual 10 m rise in sea level), the extinction of one-sixth to one-third of terrestrial species of life with a rapid 2–3 K warming (i.e. by 2050), the conversion of the Amazon rainforest to savannah or grassland with 3 K global mean warming if the mean climate becomes more El Niño-like, widespread summer drought conditions and reduction in food production in developing countries (if not elsewhere) in association with 2–3 K warming, and severe reductions in available water supply in regions that are dependent on glacial meltwater within a few decades, most of which are already highly vulnerable to water shortages.

There are two issues with regard to transient (time-varying) climatic change: (i) how fast the warming occurs, and (ii) how long the warming endures (for scenarios where radiative forcing peaks and then declines). Agricultural impacts will be largely independent of the rate and duration of climatic change (since even the fastest rates of change will be slow compared to rates of adaptation), but will instead depend on the nature and magnitude of the changes. Coral reefs may be able to adapt to higher temperatures through natural selection over successive generations if warming is slow enough, but the required rates of warming for successful adaptation are likely to be so slow that even the slowest conceivable approach to stabilization at 2 K global mean warming (i.e. by the end of this century if CO_2 asymptotes at 450 ppmv and climate sensitivity is only 2 K) would have little effect on the critical temperature thresholds. Slower warming will likely reduce losses of terrestrial species to some extent by providing more time for range shifts in regions where human obstacles do not impede migration. If one chooses a temperature threshold for unacceptable harm based on impacts on terrestrial ecosystems, this threshold could be somewhat larger if slower change is assumed. If the threshold is low, then emissions will need to be significantly reduced early in this century in order to avoid exceeding the threshold, which will have the added benefit of slowing the rate of warming and thereby increasing the threshold. The main impact dependent on the duration of warming (as well as on the magnitude) is the loss of alpine glaciers (and the associated summer runoff) and the potential triggering of the collapse of the Greenland and West Antarctic ice sheets.

Although different cultures may value different impacts differently, there are so many different negative impacts at even 1–2 K warming, and they are so pervasive, that is it reasonable to place the warming threshold beyond which unacceptable impacts occur between 1 and 2 K. However, two log-normal pdfs for this threshold will be considered here: one with a median threshold (50th percentile) of 1.5 K and a 5–95% range of 0.9–2.7 K, and the other with a median threshold of 2.5 K and a 5–95% range of 1.6–3.8 K. A log-normal distribution for the threshold of unacceptable warming is used instead of a normal distribution because, when the most likely threshold for unacceptable warming is set at 1.5 K, the log-normal distribution gives negligible probability that the threshold lies at 0.5 K or less while the normal distribution does not. The two log-normal pdfs and the corresponding cumulative pdfs are shown in figure 2, while the μ and σ values are given in table 2.

An alternative choice of the harm-threshold pdf would be a beta distribution, in which the distribution falls entirely within the interval [0, 1] that in turn can be scaled and shifted to correspond to any desired lower temperature (below which the cumulative pdf is precisely zero) and upper temperature (at which point the cumulative pdf is precisely unity). However, it will always be possible to choose a right-skewed beta pdf that gives essentially the same variation of harm with radiative forcing as a given log-normal pdf. This is because the computation of harm as a function of radiative forcing, given below, depends largely on the degree of overlap between the climate sensitivity and harm-threshold pdfs, and this also determines the extent to which differences in the tails of the distribution matter. For example, if the cumulative pdf for the harm threshold is close to 1.0 by a warming of 3 K (as in figure 2(a)), then changes in the shape of the climate sensitivity pdf beyond 3 K will have little effect on the probability of harm for radiative forcings equivalent to a CO_2 doubling or greater. Conversely, for a climate sensitivity pdf concentrated below 4.5 K, changes in the shape of the harm-threshold pdf beyond 4.5 K will have little effect on the probability of harm for radiative forcings equivalent to a CO_2 doubling or greater. Through the choice of many different climate sensitivity pdfs (figure 1) and two different harm-threshold pdfs (figure 2), a wide range of overlaps between the two distributions arises, and this allows us to assess the robustness of the final results to be presented below.

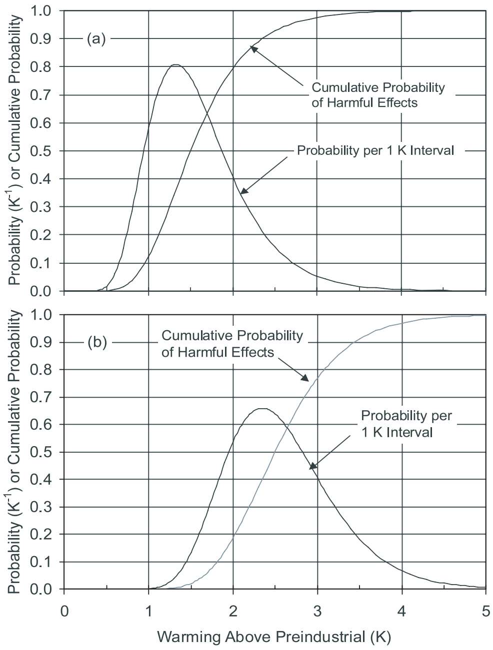

Figure 2. The two pdfs adopted here for the minimum sustained warming that causes unacceptable harm, and the corresponding cumulative pdfs. (a) The more stringent harm-threshold pdf, and (b) the less stringent harm-threshold pdf.

3. Probability of harm as a function of radiative forcing, and risk thresholds

Given the pdfs for climate sensitivity and for the harm threshold in terms of global mean temperature, one can calculate the probability that any given radiative forcing will lead to harm. In computing these probabilities, it can be assumed that the eventual global mean temperature change varies linearly with radiative forcing. Simulations with climate models indicate that this is a good approximation (valid to within 10% or better) as long as the climate system does not cross some threshold where abrupt change occurs due, for example, to a rapid reorganization of the ocean circulation.

Let $\mathrm{pdf}_{2x}(\Delta T)$ be the pdf for climate sensitivity—that is, the pdf of long-term temperature change ΔT associated with the radiative forcing of a CO_2 doubling. Then $\Delta(\Delta T_i)\mathrm{pdf}_{2x}(\Delta T_i)$ is the probability of the climate sensitivity occurring within an interval of width $\Delta(\Delta T_i)$ centred at ΔT_i. If the radiative forcing is R_f times that for a CO_2 doubling, then $\Delta(\Delta T_i)\mathrm{pdf}_{2x}(\Delta T_i)$ is the probability that the temperature change produced by this forcing lies in an interval of width $R_f\Delta(\Delta T_i)$ centred at $R_f\Delta T_i$. Let $\mathrm{Cpdf}_{\mathrm{harm}}(\Delta T_i)$ be the cumulative probability distribution for the harm threshold, that is, the probability that the threshold for harm is a temperature change of ΔT_i or less. Then, $\Delta(\Delta T_i)\mathrm{pdf}_{2x}(\Delta T_i)\cdot\mathrm{Cpdf}_{\mathrm{harm}}(R_f\Delta T_i)$ is the probability that the temperature change due to a radiative forcing of R_f times that of a CO_2 doubling falls in the interval centred at $R_f\Delta T_i$ and that this temperature change is harmful. The total probability of harm is given by this product summed over all the possible warming intervals. That is,

$$P_{\mathrm{harm}}(R_f) = \int_0^{\infty} \mathrm{pdf}_{2x}(\Delta T) \times \left(\int_0^{R_f\Delta T} \mathrm{pdf}_{\mathrm{harm}}(\Delta T')\,\mathrm{d}\Delta T'\right)\mathrm{d}\Delta T. \qquad (1)$$

Equation (1) gives the probability of harm associated with a given radiative forcing ratio R_f assuming that the climate has time to come into equilibrium with the radiative forcing.

Figure 3 shows $P_{\mathrm{harm}}(R_f)$ for all the climate sensitivity pdfs considered here; figure 3(a) gives $P_{\mathrm{harm}}(R_f)$ for the more stringent harm-threshold pdf (1.5 K median) and figure 3(b) for the less stringent harm-threshold pdf (2.5 K median). For any given combination of pdfs, the risk of harm increases with increasing forcing ratio R_f. The difference between the standard and alternative sets of climate sensitivity pdfs is large only at large risk tolerances.

In deciding on an acceptable forcing, the acceptable probability of harm must be specified. Given that the harm under consideration here involves massive species extinction and risks of death or at least of severe disruption to hundreds of millions of people, the acceptable probability of harm should be quite low. Risk thresholds of 1%, 5% and 10% are illustrated in figure 3. If the harm associated with the impacts discussed above (and to be avoided) involves the death of 10–100 million people over the next century (an optimistic assumption given the numbers-at-risk curves of Parry *et al* (2001) out of 10 billion people, then the average risk of death for any one person is roughly 1 in 1000 to 1 in 100. Thus, a probability of harm of 1% would correspond to a risk of death to individuals of 1:100 000 to 1:10 000. This is a 10- to 100-fold greater risk than the 1 in 1 000 000 threshold adopted by the US Environmental Protection Agency and the Nuclear Regulatory Commission (see Tonn 2003). The allowable GHG radiative forcing is given by the intersection of the chosen $P_{\mathrm{harm}}(R_f)$ (corresponding to particular climate sensitivity and harm-threshold pdfs) and the chosen risk tolerance. The difference in allowable radiative forcing for 1% and 10% risk tolerances is smaller the more that the climate sensitivity pdf is shifted toward large warming.

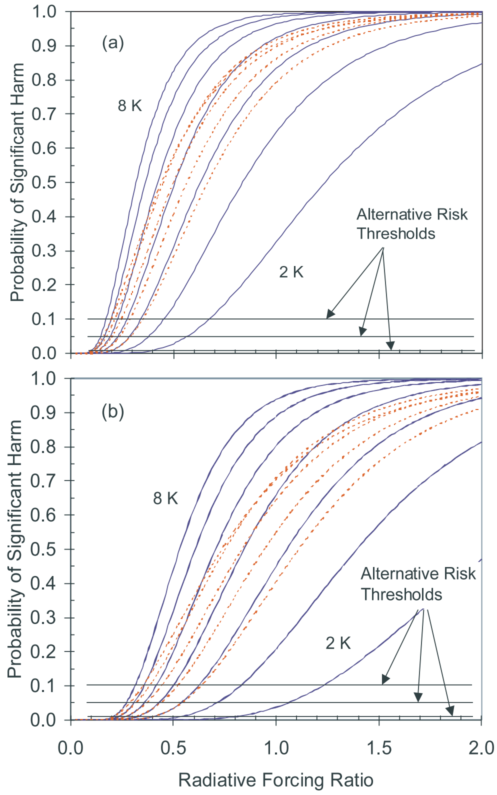

Figure 3. The probability of unacceptable harm, as a function of the radiative forcing ratio, for various climate sensitivity pdfs and for (a) the more stringent harm-threshold pdf and (b) the less stringent harm-threshold pdf. Also shown are risk thresholds of 1%, 5% and 10% probability of significant harm. The curves corresponding to climate sensitivity pdfs with 95th percentiles at 2 and 8 K are marked.

4. Permissible long-term CO_2 concentrations with equilibrium climatic change

Figure 4 gives the acceptable long-term CO_2 concentration as a function of the 95th percentile of the climate sensitivity pdf. Results are given assuming the non-CO_2 GHG plus surface albedo forcing (about 1.15 W m^{-2}) to be frozen at the present level (figure 4(a)) or frozen at half of the present level (figure 4(b)), both of which would require stringent reductions in emissions of non-CO_2 GHGs or of ozone precursors compared to business-as-usual scenarios[1]. Also given, in

[1] Of the approximate 1.15 W m^{-2} present non-CO_2 and non-aerosol forcing, 0.48 W m^{-2} is due to CH_4, 0.15 W m^{-2} to N_2O, 0.34 W m^{-2} to halocarbons and about 0.35 W m^{-2} to tropospheric ozone (Ramaswamy *et al* 2001). Stabilization of the atmospheric CO_2 concentration at 450 ppmv would require the phase-out of fossil fuel use by the end of this century and its replacement with a renewably based hydrogen economy, which in turn implies the near total elimination of tropospheric O_3 forcing (which is a by-product of fossil fuel use and biomass burning), which alone would go more than half way toward reducing non-CO_2 GHG forcing by half. Forcing by other GHGs would either have to be stabilized at the current level (N_2O, halocarbons) or modestly reduced (CH_4).

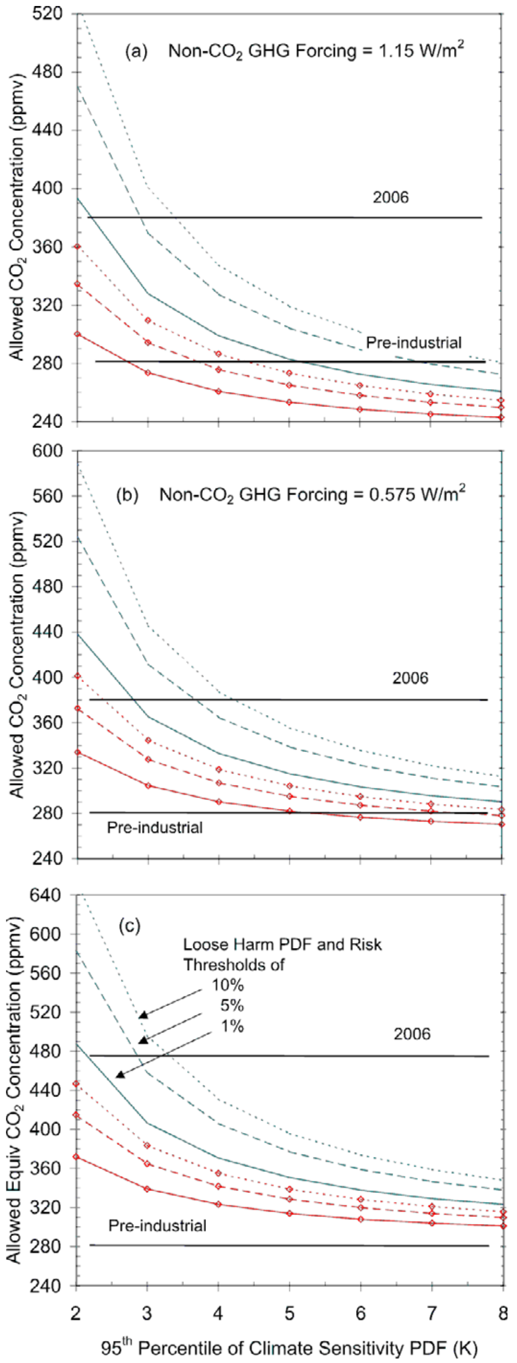

Figure 4. Maximum allowed CO_2 concentrations as a function of the 95th percentile of the climate sensitivity pdf, assuming either the more stringent harm-threshold pdf (red lines with diamonds) or the less stringent harm-threshold pdf (blues lines) and either a 1% (solid lines), 5% (long dashes) or 10% (short dashes) risk tolerance. Results are given for non-CO_2 GHG forcing frozen at either (a) the present level, (b) half the present level or (c) zero (the allowed CO_2 concentration in this case is the allowed equivalent CO_2 concentration). Also shown are the pre-industrial CO_2 concentrations and either the 2006 CO_2 concentrations (a, b) or the 2006 equivalent CO_2 concentration of about 475 ppmv (c).

figure 4(c), are results with zero non-CO_2 radiative forcing, which in this case represent the allowable equivalent CO_2 concentration (i.e. the concentration of CO_2 alone having the same radiative forcing as from all the GHGs present). Results are given for the more stringent harm-threshold pdf (red lines with diamonds) and for the less stringent harm-threshold pdf (blue lines) and for risk tolerances of 1% (solid lines), 5% (long dashes) and 10% (short dashes). Also shown is the pre-industrial CO_2 concentration of 280 ppmv and the 2006 concentration of 380 ppmv. In computing the allowable CO_2 concentrations, it has been assumed that the radiative forcing for a CO_2 doubling is 3.71 W m^{-2} and that the forcing varies with the natural logarithm of CO_2 concentration (see Harvey *et al* 1997). Results are given only for the standard set of climate sensitivity pdfs, as the difference between this set and the alternative set is negligible (as could be expected from figure 3).

For the stringent harm-threshold pdf, present non-CO_2 GHG radiative forcing and a 1% risk tolerance, the allowable CO_2 concentration varies from 300 ppmv for the climate sensitivity 95th percentile at 2 K, to 243 ppmv for the 95th percentile at 8 K. All of these are far below the 2006 concentration of 380 ppmv, and for most climate sensitivities are below the pre-industrial CO_2 concentration of 280 ppmv. The latter is due to the fact that the non-CO_2 GHG forcing alone is able to yield a greater than 1% chance of unacceptable impacts when there is at least a 5% chance of a climate sensitivity of 2.5 K or greater. For the less stringent harm-threshold pdf, present non-CO_2 GHG radiative forcing and a 10% risk tolerance, the allowable CO_2 concentration varies from 528 to 281 ppmv. It is interesting to note that beyond a 95th percentile of 4–5 K there is very little further decrease in the allowable CO_2 concentration. Thus, in terms of DAI, the difference between the conventional climate sensitivity range of 1.4–4.5 K and the more recent pdfs that are shifted toward higher sensitivities is not important. Finally, if non-CO_2 GHG radiative forcing could be reduced to half the present forcing, then the allowable CO_2 concentrations range from 334 to 270 ppmv (stringent harm-threshold pdf and 1% risk tolerance) or from 588 to 313 ppmv (less stringent harm-threshold pdf and 10% risk tolerance).

5. Accounting for peak warming being less than equilibrium warming if GHG forcing declines after peaking

If fossil fuel CO_2 emissions were to be reduced to zero by the end of this century, and stringent reductions in emissions of other GHGs were to be achieved, then total radiative forcing would decrease. Due to the delay effect of the oceans, global mean temperature would not reach equilibrium with the peak CO_2 concentration before beginning to decrease. Thus, for a given temperature constraint, the peak CO_2 concentration can be somewhat larger than deduced above based on the assumption of equilibrium climatic change. The additional allowed CO_2 concentration will be called the CO_2 *climate-disequilibrium credit*.

To calculate this credit, we first estimate the difference between peak realized warming and peak equilibrium warming (i.e. the warming that would occur in equilibrium with the

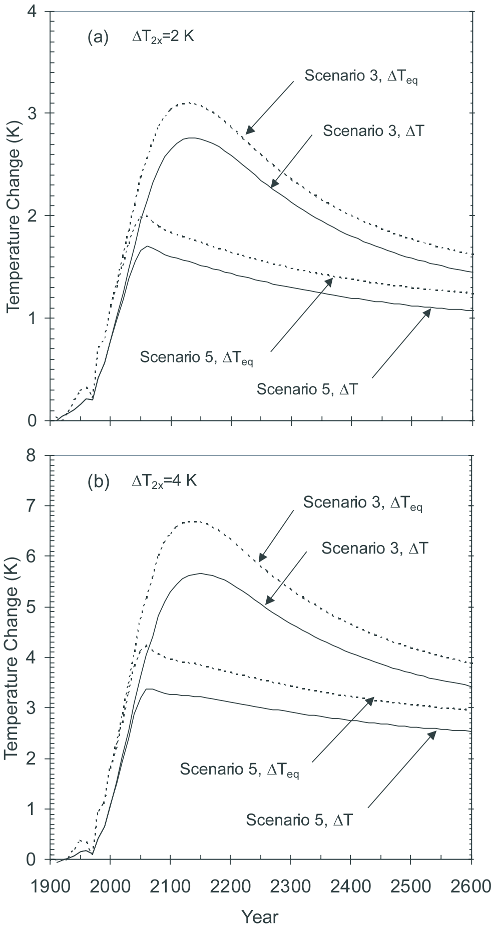

Figure 5. Illustration of the difference between realized and equilibrium global mean temperature change of emission scenarios 3 and 5 of Harvey (2004) and for climate sensitivities of 2 and 4 K, as computed with a low-resolution coupled atmosphere–ocean climate–carbon cycle model.

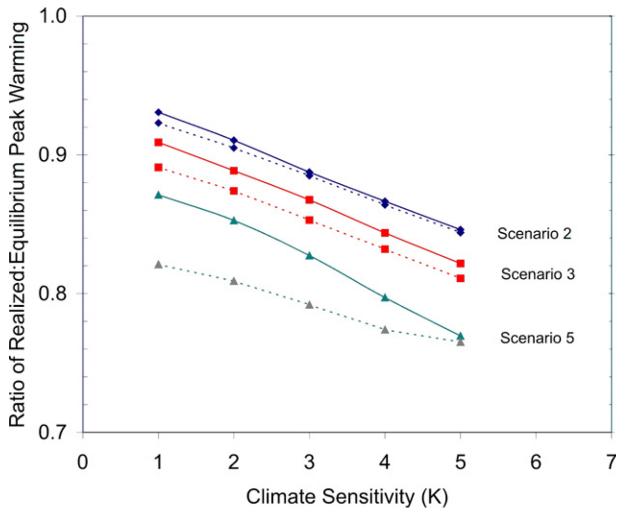

Figure 6. Ratio of maximum realized warming to maximum equilibrium warming as computed with a low-resolution coupled atmosphere–ocean climate model for three emission scenarios from Harvey (2004) and for various climate sensitivities. Solid lines are based on maximum annual realized warming and dashed lines on maximum 100 year mean realized warming.

peak radiative forcing) using the coupled-climate carbon cycle model of Harvey and Huang (2001) and Harvey (2001). This is a quasi-one-dimensional model that simulates the absorption of CO_2 and heat by the oceans in response to a given emission scenario. The oceanic mixing parameters (overturning circulation flux and diffusion coefficients) have been thoroughly validated using a variety of steady-state and transient tracer data (temperature, carbon isotopes, dissolved O_2, nutrients and alkalinity).

For climate sensitivities ranging from 1 to 5 K, and for emission scenarios 2, 3 and 5 of Harvey (2004) (having peak radiative forcings of 10.1, 6.2 and 4.0 W m^{-2}, respectively), I have computed the peak annual realized warming and the peak 100 year mean warming as a fraction of the peak equilibrium warming (the 100 year mean warming is considered here for illustrative purposes, in recognition of the fact that impacts depend on the duration as well as the magnitude of warming). Time-varying realized and equilibrium global mean warmings are compared for scenarios 3 and 5 for climate sensitivities of 2 and 4 K in figure 5. Even after the equilibrium warming begins to decline (due to falling radiative forcing), the realized warming remains smaller than the equilibrium warming due to a small but long-term heat flux (of about 0.2–0.3 W m^{-2}) into the deep ocean. Ratios of annual peak realized warming to annual peak equilibrium warming are presented in figure 6 for all three scenarios. For scenario 2, emissions reach a broad plateau and then decrease slowly, so the peak annual warming is a relatively large fraction (about 0.86–0.94) of the peak equilibrium warming. For scenario 5, CO_2 emissions drop to zero by 2070 and stringent reductions in emission of other GHGs occur, so the radiative forcing falls rather rapidly during the second half of the 21st century, and the peak warming is only about 0.78–0.87 times the peak equilibrium warming. The ratio decreases slightly with increasing climate sensitivity due to the well-known increase in temperature response timescale with climate sensitivity (e.g. Harvey 1986). Because temperature falls very slowly after the peak (as illustrated in figure 5), the ratio of maximum 100 year mean warming to peak equilibrium warming is only slightly smaller than the ratio of peak annual warming to peak equilibrium warming (figure 6, dashed lines).

Equation (1) gives the probability of harm assuming that the equilibrium warming ($R_f \Delta T$) for a given climate sensitivity and radiative forcing is reached, so the harm-threshold pdf is integrated up to the temperature $R_f \Delta T$. Due to the lag effect of the oceans in the simulations performed here, only some fraction r of the peak equilibrium warming is reached, so we need integrate the harm-threshold pdf only up to $r R_f \Delta T$. Because the context here is one in which emissions are reduced in order to avoid DAI, we shall compute r based on the ratio of maximum 100 year mean warming to maximum equilibrium warming obtained for scenario 5. Thus, the integration limit of $R_f \Delta T$ in equation (1) is replaced with a limit ranging from $0.82 R_f \Delta T$ at a climate sensitivity of 1 K to $0.78 R_f \Delta T$ at a climate sensitivity of 5 K and (by linear

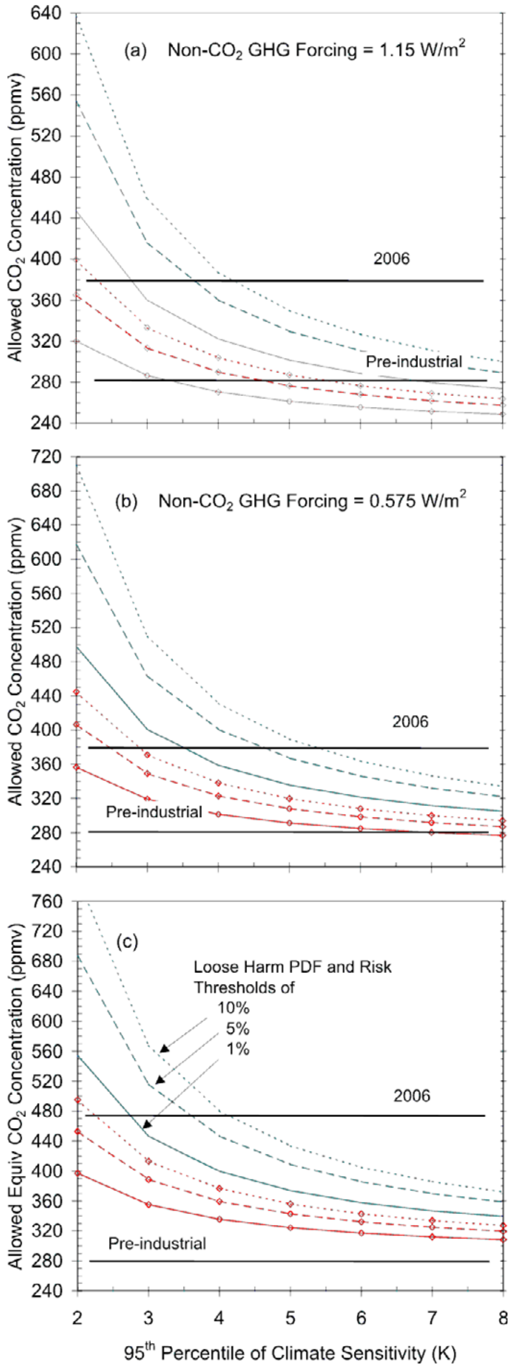

Figure 7. Same as figure 4, except that realized warming is assumed to reach a fraction of the peak equilibrium warming ranging from 0.82 at a climate sensitivity of 1 K to 0.73 at a climate sensitivity of 10 K.

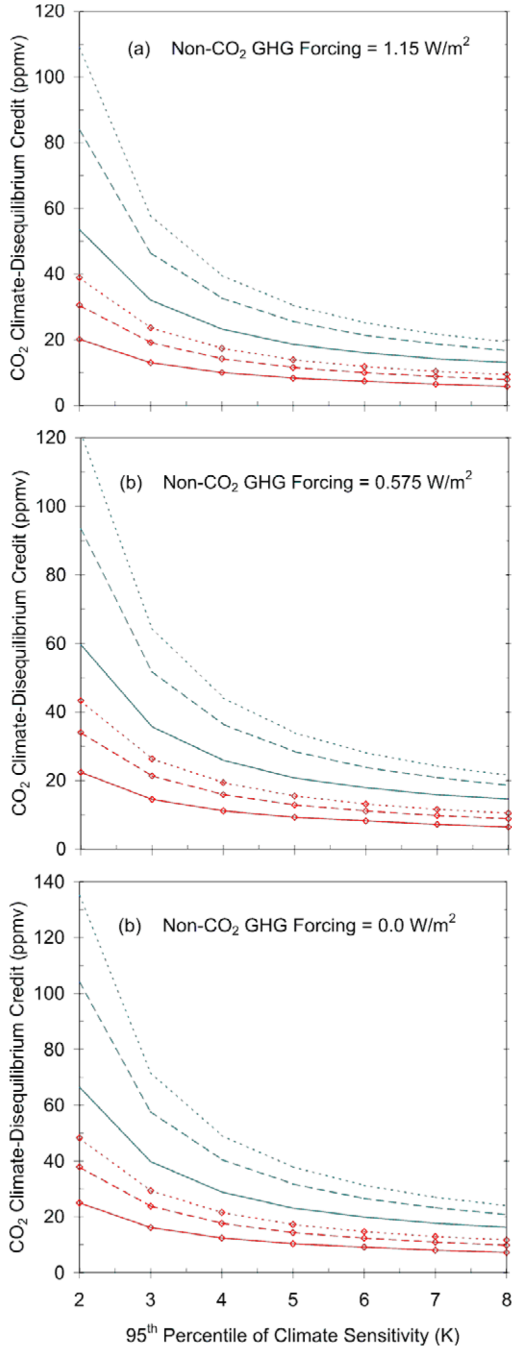

Figure 8. CO_2 climate-disequilibrium credit as a function of the 95th percentile of the climate sensitivity pdf, assuming either the more stringent harm-threshold pdf (red lines with diamonds) or the less stringent harm-threshold pdf (blues lines) and either a 1% (solid lines), 5% (long dashes) or 10% (short dashes) risk tolerance. Results are given for non-CO_2 GHG forcing frozen at either (a) the present level, (b) half the present level or (c) zero (the CO_2 climate disequilibrium credit in this case is the credit in terms of equivalent CO_2 concentration).

extrapolation) $0.73 R_f \Delta T$ at a climate sensitivity of 10 K. Figure 7 shows the resulting allowed peak CO_2 concentration for the same sets of conditions as in figure 4. Figure 8 shows the differences between figures 4 and 6 in the allowed CO_2 concentrations. This is the CO_2 climate-disequilibrium credit. For the pdf_{2x} with a 95th percentile at 4.5 K, the credit is 20–40 ppmv for the lenient $\mathrm{pdf}_{\mathrm{harm}}$, and 10–20 ppmv for the stringent $\mathrm{pdf}_{\mathrm{harm}}$, in both cases assuming non-CO_2 GHG radiative forcing equal to half the present value.

The disequilibrium is smaller the lower the risk tolerance and the more that pdf_{2x} is shifted to higher climate sensitivities.

To understand this behaviour, note that the additional radiative forcing allowed due to climate disequilibrium is given by

$$\Delta R = R\left(\frac{1}{r} - 1\right) \tag{2}$$

where R is the allowed radiative forcing without any disequilibrium credit. For a specified allowable warming of ΔT_{limit}, climate sensitivity ΔT_{2x} and radiative forcing for a CO_2 doubling of R_{2x}, R is given by

$$R = \left(\frac{\Delta T_{\text{limit}}}{\Delta T_{2x}}\right) R_{2x}. \tag{3}$$

Thus,

$$\Delta R = \left(\frac{\Delta T_{\text{limit}}}{\Delta T_{2x}}\right)\left(\frac{1}{r} - 1\right) R_{2x}. \tag{4}$$

Thus, with a smaller ΔT_{limit} (or a more stringent pdf_{harm} or a smaller risk tolerance) or a larger climate sensitivity, a smaller additional forcing and hence a smaller additional CO_2 increase is allowed.

6. Summary and concluding comments

Evidence reviewed elsewhere indicates that the threshold for significant and widespread negative impacts due to global warming probably falls somewhere between 1 and 2 K sustained warming, and hence that a sustained warming exceeding this amount would not be acceptable to many or most people (depending on individual values). It is argued here that the probability of exceeding the threshold of unacceptable warming should be quite low, perhaps around 1% and certainly no more than 10%. Given a median threshold for unacceptable harm of 1.5 K global mean warming (stringent case) or 2.5 K (lenient case), acceptable risks of 1–10% for exceeding a global mean warming that causes unacceptable harm, and assuming that non-CO_2 GHG radiative forcing can be reduced to half its present value, the following is found: (1) for a climate sensitivity pdf with a 95th percentile at 2 K global mean warming, the allowable CO_2 concentration ranges from about 330 ppmv (1% risk tolerance and stringent harm-threshold pdf) to 590 ppmv (10% risk tolerance and less stringent harm-threshold pdf). (2) As the 95th percentile of the climate sensitivity pdf increases to 4.5 K (corresponding to the longstanding consensus), the allowable CO_2 concentration is 290–370 ppmv. (3) As the climate sensitivity pdf is shifted to larger warming, there is relatively little further reduction in the allowable CO_2 concentration for the harm-threshold pdfs considered here; when the 95th percentile increases to 8 K, the allowable CO_2 concentration drops to about 270–310 ppmv. If non-CO_2 GHG radiative forcing is frozen at its present value, then the allowable CO_2 concentration is about 30 ppmv less.

All of these results assume that the allowed CO_2 concentration is reached and then held without first overshooting it, so that the realized warming corresponds to the equilibrium warming associated with the allowed CO_2 concentration. In reality, CO_2 concentration could peak and then decline if emissions are reduced to zero, so the peak realized warming would be less than the equilibrium associated with the peak CO_2 concentration. This allows a peak CO_2 concentration that is 10–40 ppmv higher than the concentrations that are permitted in the long term, depending on the choice of harm-threshold pdf and risk tolerance.

The most important result of this analysis is that the present CO_2 concentration of 380 ppmv already represents DAI, or is close to representing DAI. This is a robust result, in that it is true for a very wide range of climate sensitivity and harm-threshold pdfs, risk tolerances and assumptions concerning non-CO_2 GHG radiative forcing. It is also true even if allowance is made for CO_2 concentration peaking and then declining, such that realized warming does not fully reach peak equilibrium warming, and it is true even if a minimum duration of 100 year warming beyond the adopted threshold temperature is assumed to be required before unacceptable harm occurs.

Acknowledgments

This paper benefited greatly from the comments of two anonymous reviewers.

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