# Uncertainties in global warming science and near-term emission policies

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## Abstract

It is argued here that stringent, early emission reductions are necessary in order to minimize 'dangerous anthropogenic interference in the climate system' (DAI), the stated Objective of Article 2 of the UNFCCC (United Nations Framework Convention on Climate Change). Given probability distribution functions (pdfs) for climate sensitivity and the temperature threshold for harm consistent with currently available evidence, and accepting a 10% risk of unacceptable damage as the threshold for 'danger', it is not possible to avoid DAI. Having adopted a precautionary approach in setting emission trajectories, the possibility arises that future resolution of uncertainties concerning climate sensitivity and the harm threshold may show the climate sensitivity to be low (1–2 K) and the harm threshold high (2 K rather than 1 K). Using a simple coupled climate-carbon cycle model, it is shown that if the climate sensitivity were to be definitively determined to be 2 K in 2020, then the emission reductions achieved by that time and planned for the next two decades are still fully needed. Only if climate sensitivity is very low (1 K) and the harm threshold is high (2 K) would the emissions achieved by 2020 not have been fully necessary. However, this would still lead to changes in ocean chemistry that are likely to be highly detrimental to marine life. Thus, when the full spectrum of impacts is considered, there is no plausible set of assumptions under which stringent near-term emission reductions are rendered unnecessary.

*Keywords*: Climate policy; Climate sensitivity; Risk tolerance; Emission targets; Near-term planning

## 1. Introduction

Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC) reads:

> The ultimate objective of this Convention ... is to achieve ... stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened, and to enable economic development to proceed in a sustainable manner.

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Anthropogenic interference in the climate system by greenhouse gases (GHGs) arises both through radiative forcing (heat trapping) leading to climatic change and, in the case of $CO_2$, through changes in ocean chemistry. The UNFCCC does not state what set of GHG concentrations constitutes 'dangerous anthropogenic interference' (DAI). However, because Article 2 presents a risk-averse framework (avoiding 'danger'), concentration limits must be determined based on plausible worst-case outcomes (where 'plausibility' is defined in terms of some minimum probability). Thus, for climate-related impacts, if 2 K warming is regarded as the maximum tolerable warming, if there is a 10% chance of the climate sensitivity (the eventual global mean warming for a $CO_2$ doubling) exceeding 4 K, and if one wants to run no more than a 10% chance of exceeding 2 K warming, then total GHG radiative forcing (heat trapping) will have to be limited to half that for a $CO_2$ doubling (assuming that warming varies linearly with forcing, which is a good approximation until and unless abrupt changes in the climate system occur). However, if one wants to run no more than a 2% chance of exceeding 2 K warming, and if there is a 2% probability that the climate sensitivity exceeds 8 K, then the radiative forcing has to be limited to only one-quarter that of a $CO_2$ doubling. With a 2% risk tolerance, any larger GHG increases would constitute DAI *even if* the true climate sensitivity later turns out to be much smaller. This is because 'danger' arises from the *possibility* (above some threshold probability) of unacceptably large climate change.

Thus, to know how strongly GHG emissions should be reduced, we need merely to determine plausible *upper limits* to the climate sensitivity, rather than a 'best-guess' climate sensitivity. Similarly, to determine the temperature increases that pose a threat to ecosystems, food production or sustainable development, we need merely determine plausible upper limits to their sensitivity.

Given uncertainty in the true climate sensitivity and in the global mean temperature threshold for significant harm (sufficient to violate Article 2 of the UNFCCC, and thus deemed to incur unacceptable impacts), allowable GHG concentrations can be determined if the uncertain climate sensitivity and harm threshold can be represented by probability distribution functions (pdfs). The pdfs can be represented by the temperature change or temperature harm threshold thought to be equalled or exceeded with likelihoods of 5% and 95%. The conventional climate sensitivity pdf has a 5–95% range of 1.5–4.5 K, and this is adopted here although some recent pdfs are strongly skewed toward high sensitivities (with 95th percentiles of 6–9 K). Evidence reviewed by Harvey (2007a) and Warren (2006) indicates that significant harm is likely to occur at a global mean warming somewhere between 1 K and 2 K. Here, a harm-threshold pdf with a 10–90% range of 1.0–2.5 K is adopted (Figure 1a).

The climate sensitivity and harm-threshold pdfs can be combined to give the probability of harm as a function of the GHG radiative forcing (Figure 1b). There has been relatively little discussion of acceptable probabilities for significant harm due to global warming. Inasmuch as the potential harm involves irreversible losses of ecosystems, extinction of a significant fraction of species of life on Earth, and the death of hundreds of millions of people, the appropriate risk tolerance should be quite low. The choice of risk tolerance is fundamentally a *moral judgement* because the people deciding on the risk level (i.e. the major greenhouse gas emitters today) are largely not those who will be placed at risk (i.e. future generations, people in developing countries, and other species of life). A 10% risk is shown by the horizontal line in Figure 1, and the intersection of this curve with the probability-of-harm curve gives the allowed GHG radiative forcing if a 10% risk is considered acceptable. For a 10% risk tolerance, the radiative forcing ratio should not exceed 30% that of a $CO_2$ doubling using the given climate sensitivity and harm-threshold pdfs. The current radiative forcing due to GHGs is already 67–89% that for a $CO_2$ doubling (about 2.5–3.3 $W/m^2$ compared with a doubling forcing of 3.71 $W/m^2$) and poses a 40–75% risk of causing unacceptable harm, a risk that is surely far in excess

 

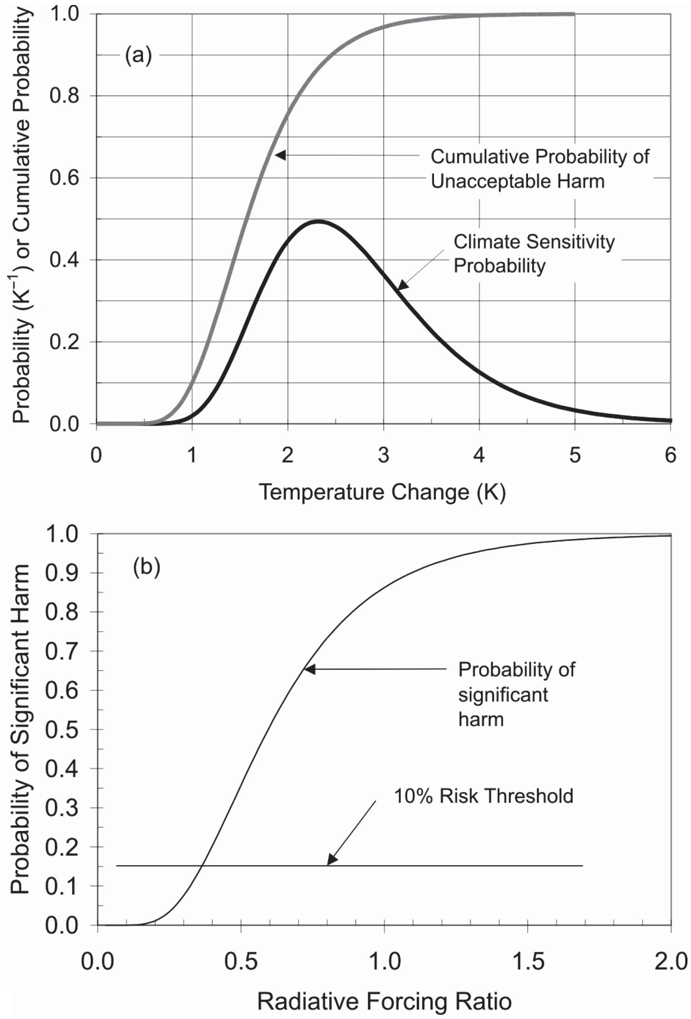


Figure 1. (a) The probability distribution function for climate sensitivity and the cumulative probability distribution function for the threshold of unacceptable harm adopted here. (b) The resulting probability of harm as a function of the GHG radiative forcing (given as a ratio to the radiative forcing for a $CO_2$ doubling). The 2006 GHG radiative forcing (2.50–3.3 W/m$^2$) was 67–89% of that for a $CO_2$ doubling.

of what most people would consider to be ‘dangerous’, given the seriousness of the potential consequences. Thus, current GHG concentrations *already violate* Article 2 of the UNFCCC. This is a robust result, valid for a wide range of assumptions concerning the climate-sensitivity and harm-threshold pdfs and concerning the risk tolerance, as shown by Harvey (2007a, 2007b).

If current GHG concentrations already violate Article 2 of the UNFCCC, then immediate and stringent emission reductions are required. This is not required in order to comply with Article 2, but in order to minimize the length and duration of non-compliance. Stringent emission reductions are required *because of* present uncertainties, combined with the risk-averse nature of Article 2. The possibility arises, however, that at some future date, the climate sensitivity will be determined to be near the low end of the currently accepted plausibility range, and the threshold for unacceptable harm placed near the high end of the 1–2 K range. A substantial literature has assessed the assumed tradeoff between (1) the risk of making early emission reductions that turn out to have been unnecessary (because the climate or ecosystem sensitivity turns out to be smaller than thought at the time of the emission reductions), versus (2) the risk of having to make faster and/or deeper reductions later because initial emission reductions were delayed until uncertainties were reduced (examples include Schlesinger and Jiang, 1991a, 1991b; Hammitt et al., 1992; Chichilnisky and Heal, 1993; Lempert et al., 1996; Ulph and Ulph, 1997; Webster, 2002). The dilemma is posed – is it better to risk error (1) or error (2)?

This article shows that this is a false dilemma, in that if a near-term emission constraint far in excess of what is usually contemplated at present were adopted (namely, returning global emissions to the 2010 level by 2020 and continuing to head downwards), there is no plausible outcome of present uncertainties that would render this near-term trajectory unnecessary. This conclusion is reached using a simple coupled climate-carbon cycle model to examine the retroactive implications for emissions during the period 2005–2020 of a hypothetical definitive determination in 2020 that the climate sensitivity ($\Delta T_{2x}$) is only 1 K or 2 K, combined with a hypothetical determination (through political consensus) that the 'safe' global mean warming is 1 K or 2 K (these being plausible lower and upper bounds to the acceptable 'safe' warming based on current knowledge).

## 2. Illustrative scenarios

The coupled climate-carbon cycle model of Harvey and Huang (2001) and Harvey (2001) is used to investigate the impact on global mean temperature of various GHG emission scenarios for various assumptions concerning climate sensitivity ($\Delta T_{2x}$). This is a model of intermediate complexity that simulates the absorption of $CO_2$ by the oceans and terrestrial biosphere, the chemistry of carbon in the oceans, and the processes of mixing of heat and carbon in the oceans. The model as formulated for the simulations presented here has a very weak positive climate-carbon cycle feedback, and so is biased in an optimistic direction. The reference case assumes that $\Delta T_{2x}$ = 4 K, as this represents a plausible (but not extreme) upper limit to $\Delta T_{2x}$ and would therefore (under Article 2) form a reasonable basis for emissions policy. We consider a stringent emission reduction scenario (described below) which, however, is unable to prevent dangerous climatic change if $\Delta T_{2x}$ = 4 K. We then determine at which point emissions can be stabilized (rather than continuing a downward trajectory) if $\Delta T_{2x}$ is determined to have successively smaller values.

### *2.1. Risk-averse GHG emission scenarios*

We consider three alternative emission scenarios for fossil fuel $CO_2$, methane and nitrous oxide, shown in Figure 2, along with significant constraints on land-use $CO_2$ emissions, halocarbons and tropospheric ozone (the details of which are unimportant). Focusing on fossil fuel $CO_2$, in Scenario A, emissions rise to 7.5 Gt C/year by 2010, return to this level by 2020, and drop to zero by 2080. In Scenario B, emissions decrease to 5.5 Gt C/year (in 2040), and are frozen thereafter, while in Scenario C, emissions are frozen at the 2020 level of 7.5 Gt C/year. Figure 3 (a, b) compares the radiative forcings by $CO_2$ and non-$CO_2$ GHGs for the three scenarios. $CO_2$ radiative forcing peaks at 2.45 W/m$^2$ in 2060 in Scenario A and rises to 3.24 W/m$^2$ and 3.58 W/m$^2$ in Scenarios B and C, respectively. Non-$CO_2$ GHG forcing is stabilized at 1.4 W/m$^2$ between 2000 and 2030 in all three scenarios, then declines to 1.0 W/m$^2$ and 1.14 W/m$^2$ by 2100 in Scenarios A and B, respectively, and rises to 1.6 W/m$^2$ by 2100 in Scenario C.

 

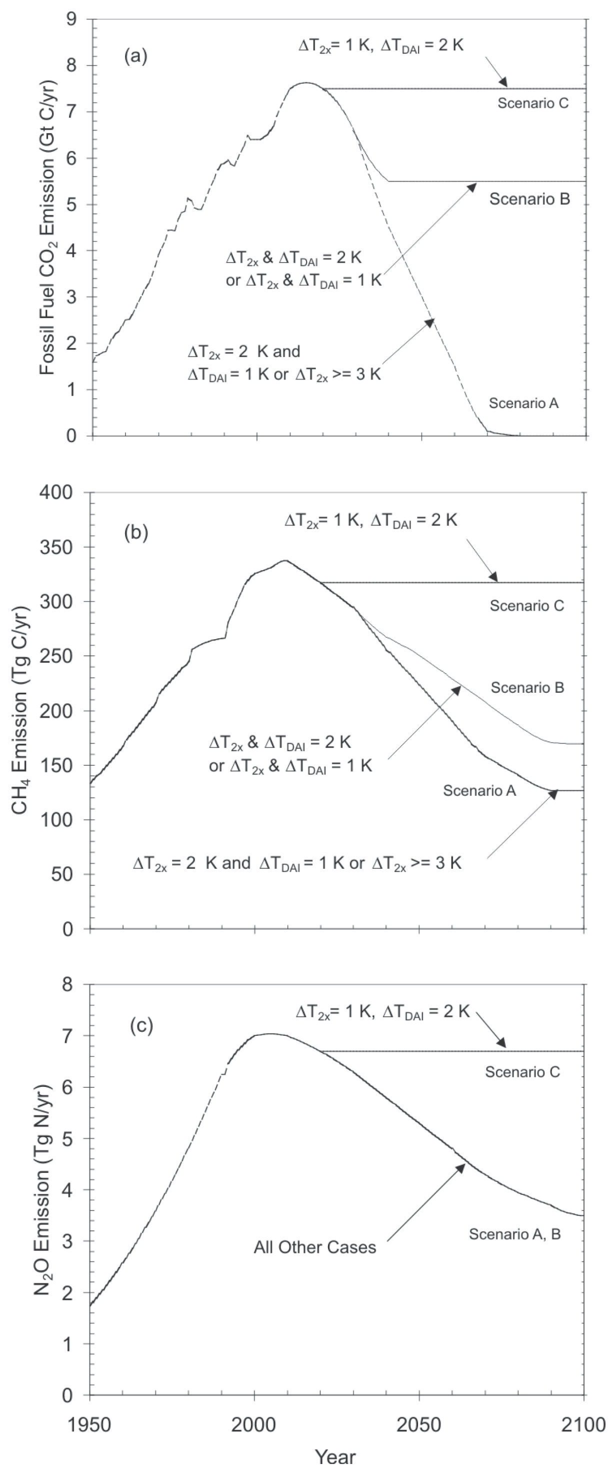


Figure 2. Emission scenarios considered here for (a) fossil fuel $CO_2$, (b) total anthropogenic $CH_4$, and (c) anthropogenic $N_2O$.

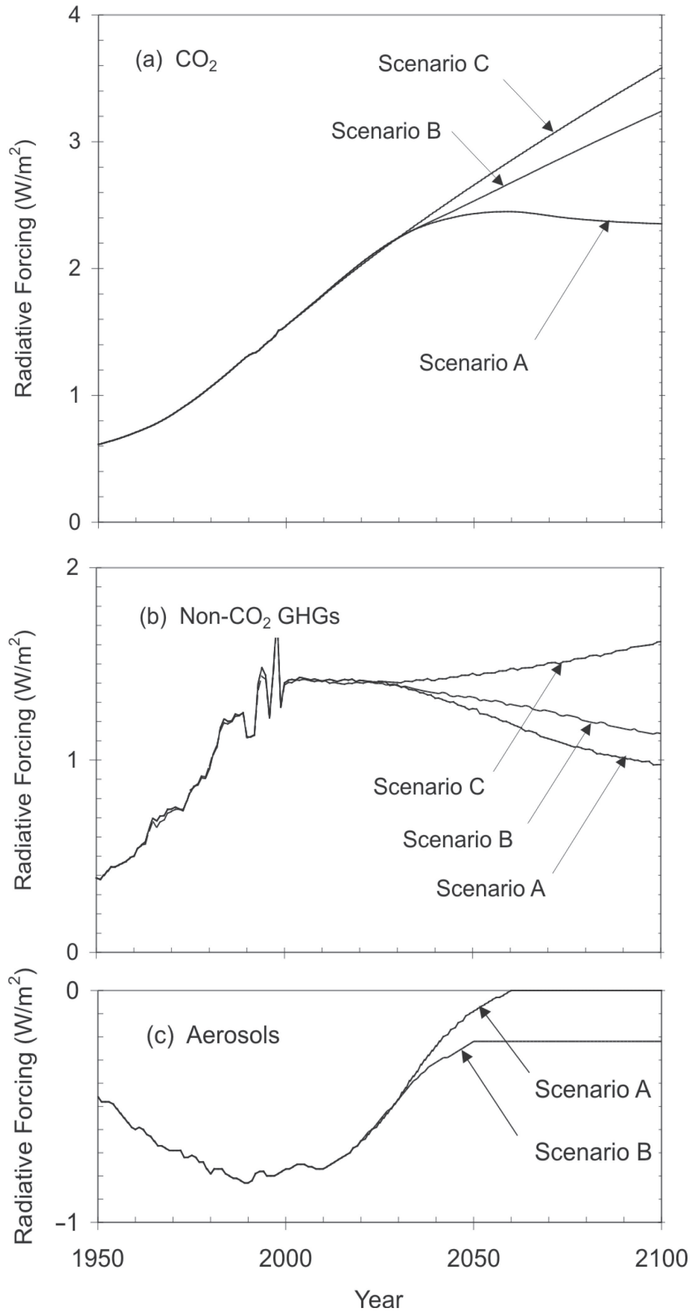


Figure 3. Radiative forcing for the various emission scenarios. (a) $CO_2$, (b) non-$CO_2$ GHGs, and (c) anthropogenic aerosols.

### *2.2. Variation of assumed aerosol forcing with climate sensitivity*

A close fit to the decadal and longer timescale variations in hemispheric and global mean climate over the past century can be obtained using a climate sensitivity ranging from 1 K to 4 K, if forcing by volcanic aerosols and solar variability is included, and if it is assumed that the net effect of anthropogenic aerosols (sulphate, nitrate, organic carbon, absorbing carbon) was to offset 0%, 30%, 40% or 60% of the GHG heating in 1990 for climate sensitivities of 1 K, 2 K, 3 K and 4 K, respectively (Harvey and Kaufmann, 2002). These forcings are adopted here.

As for the future, it is assumed that the ratio of sulphur to $CO_2$ emissions falls by a factor of four between 2000 and 2050. The aerosol forcings associated with GHG emission Scenarios A and B and for a climate sensitivity of 2 K are shown in Figure 3c (Scenario C is considered only in association with a climate sensitivity of 1 K, for which the assumed net aerosol forcing is zero). Aerosol forcings decrease in Scenarios A and B, but the impact on simulated temperature change is not large because the assumed peak aerosol forcing is not large if the climate sensitivity is 2 K.

### *2.3. Temperature results*

Figure 4a shows the global mean temperature change up to 2100 for Scenario A for a variety of cases. The top curve in Figure 4a (climate sensitivity 4 K) shows that, despite stringent emission reductions, global mean warming peaks at 3.4 K. Inasmuch as this exceeds what most would regard as a safe amount of warming, this constitutes dangerous climatic change. Given the non-negligible probability that the climate sensitivity could indeed be at least 4 K, the radiative forcing in this scenario constitutes DAI. Given that extremely stringent emission reductions were assumed for this scenario, it follows that it is not possible to avoid DAI. It may turn out, if the climate sensitivity is relatively low, to be possible to avoid dangerous climatic change (having potentially harmful effects), but the UNFCCC aims to avoid dangerous *interference* in the climate system. Interference in the climate system arises from the forcing related to GHG concentration, one step prior to climatic change in the cause–effect chain.

The dashed curve in Figure 4a shows the variation in global mean temperature when emission Scenario A is combined with hypothetical sequestration of bioenergy carbon (ramping up to 3 Gt C/year by 2050 and then sustained at 3 Gt C/year), for a climate sensitivity of 4 K. The peak warming is reduced to about 3.1 K, and the global mean temperature increase has fallen to 2.7 K by 2100 – still well above safe levels. Also shown in Figure 4a are the results for a climate sensitivity of 3 K and the same emission and sequestration scenarios. Global mean warming peaks at 2.3 K in 2060 before decreasing to 2.0 K by 2100.

Thus, the UNFCCC – endorsed by almost every country in the world – implies that the most stringent possible reduction in emissions of all GHGs, combined with an early end to net deforestation, should begin immediately. The issue is not whether or not we can avoid DAI (we can't), but whether or not we can avoid dangerous climatic change. To reiterate, the concentrations reached even with stringent reductions are dangerous because of the non-negligible possibility that the climate sensitivity is sufficiently high (3–4 K) that significant harmful impacts will occur, not because the climate sensitivity is necessarily that high.

We next consider the possibility that, by 2020, it is definitively determined that the climate sensitivity is no more than 2 K – even though a confident determination would be unlikely, not least due to the difficulty of disentangling transient from equilibrium sensitivities (Harvey, 2000, Ch. 9; Senior and Mitchell, 2000; Watterson and Dix, 2005). Results are shown in Figure 4b. Despite the finding of modest climate sensitivity, emissions must continue to fall for another 20 years, before being stabilized at 5.5 Gt C/year in 2040.[1] Planned bioenergy carbon sequestration that would otherwise begin in 2020 can be cancelled. If 1 K is regarded as a safe amount of

 

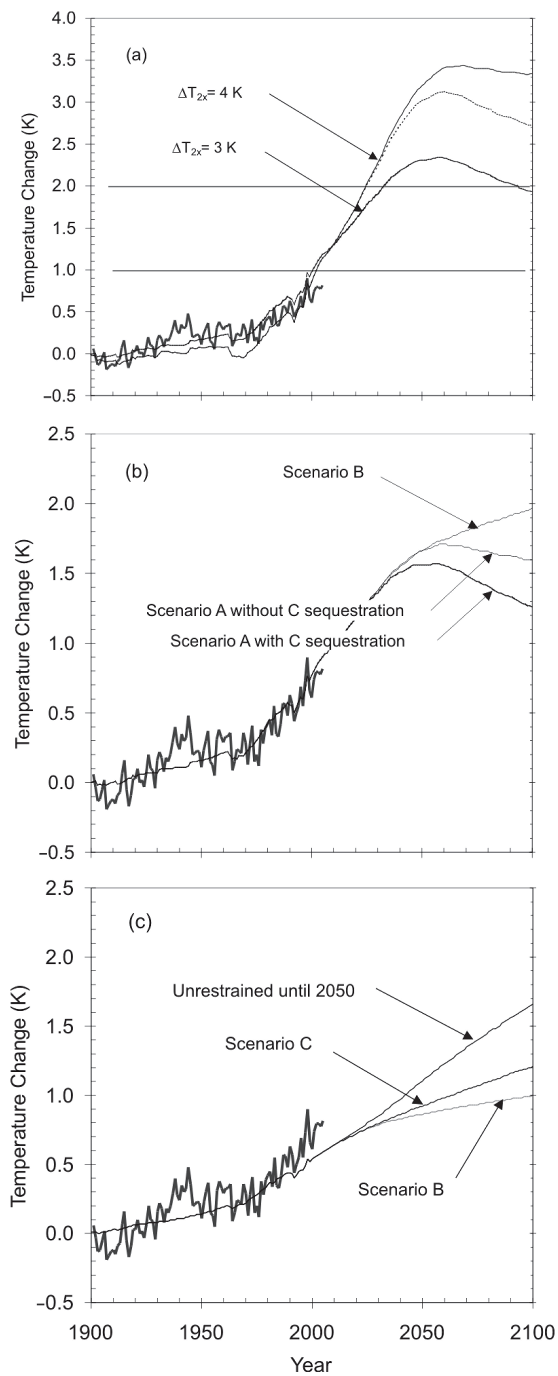


Figure 4. Global mean temperature warming for various climate sensitivities and emission/sequestration scenarios over the period 1900–2100 (thin lines), and observed global mean warming over the period 1900–2005 (thick line). (a) For climate sensitivities of 4 K and 3 K, with C sequestration assumed for the lower 4-K case and for the 3-K case. (b) For a climate sensitivity of 2 K. (c) For a climate sensitivity of 1 K. Observed warming is taken from the website of the Climate Research Unit, University of East Anglia (http://www.cru.uea.ac.uk/).

 

warming, then it is not possible to avoid dangerous climatic change, and the stronger measures with carbon sequestration after 2020 are still required. In both cases, the emission reductions between 2005 and 2020 are still necessary. That is, the 'discovery' in 2020 that the climate sensitivity is only 2 K (rather than potentially 4 K or even larger) *has no implications concerning GHG emission policy up to at least 2020: the same near-term stringent reductions in emissions are still required*. Rather, the implications concern the impacts of the unavoidable concentration increases that occur in spite of stringent emission reductions.

Lastly, we consider the possibility that the climate sensitivity is determined to be only 1 K in 2020. If the allowable warming is 1 K, further emission reductions – down to about 5.5 Gt C/year – are still required after 2020, but not sequestration. Again, the stringent emission reductions between 2005 and 2020 still turn out to have been necessary, and indeed must be accompanied by further reductions in order to prevent unacceptable harm. Only if the allowable warming is 2 K do the emission reductions undertaken between 2005 and 2020 turn out to be unnecessary. In this case, no restraints on fossil fuel emissions are required until well after 2050 (the uppermost curve in Figure 4c). Global mean temperature has warmed by 1.66 K by 2100, and would stabilize at 2 K in the following century if $CO_2$ emissions were to begin decreasing in 2100. This is the only combination where the stringent emission reductions undertaken between 2005 and 2020 turn out to have been unnecessary as far as impacts through climatic change are concerned. However, the combination of very low climate sensitivity (1 K) and a high (2 K) threshold for harm is an unlikely combination. In every other case considered here, stringent emission reductions until at least 2040 are required.

### *2.4. Impact on ocean chemistry*

Not considered up to this point is the impact of increasing atmospheric $CO_2$ concentration on ocean chemistry. This impact is essentially independent of climate sensitivity and the harm-threshold pdfs that have underpinned the analysis until this point.

Surface waters of the oceans are presently supersaturated with respect to calcium carbonate ($CaCO_3$) – the structural material of coral and of the calcareous microorganisms which occur at the base of the marine food chain. The absorption of $CO_2$ by the oceans reduces the degree of supersaturation by reducing the $CO_3^{2-}$ concentration (which is consumed through the reaction $CO_2 + H_2O + CO_3^{2-} \rightarrow 2\ HCO_3^-$). Figure 5 shows the variation in the degree of supersaturation of ocean surface waters with respect to calcite (one of two forms of $CaCO_3$) in polar and non-polar regions for the last scenario ($CO_2$ emissions frozen at 17.5 Gt C/year after 2050) and for Scenario A ($CO_2$ emissions dropping to zero by 2080). $CO_3^{2-}$ concentration decreases by 45% (non-polar regions) and 55% (polar regions) for the high emission case, but by only 17% and 27%, respectively, for the low emissions scenario. Orr et al. (2005) obtain essentially the same decreases in polar and non-polar regions using a three-dimensional model. The large decreases in the calcite supersaturation obtained with high emissions are almost certain to damage marine ecology and productivity (Orr et al., 2005; Ruttimann, 2006). Thus, impacts on ocean chemistry also provide a significant constraint on allowable $CO_2$ emissions, such that near-term emission reductions are required even in the unlikely case that climate sensitivity is very low (1 K) and the harm threshold high (2 K). Indeed, if one regards the potential impacts of the changes in ocean chemistry alone to be so serious as to warrant preventative measures, then the climate sensitivity and all the potential impacts through changes in climate are irrelevant to the choice of the appropriate emission policy.

 

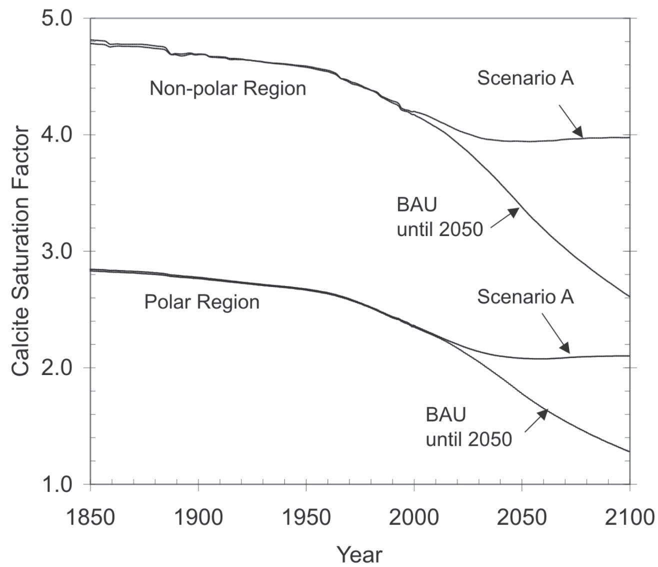


Figure 5. Variation in global mean mixed layer supersaturation with respect to calcite for the high $CO_2$ emission scenario (unrestrained until 2050, shown by the lower curve of each diverging pair) and for Scenario A (shown by the upper curve of each diverging pair).

An important policy implication is that the initial stages (lasting 2–3 decades) of what, by current standards, would be regarded as drastic emission reductions, can proceed with almost no risk that these reductions will turn out to have been unnecessary. Furthermore, and as has been well documented elsewhere, these emission reductions provide significant economic co-benefits through reduced air pollution damage (de Leo et al., 2001; Syri et al., 2001; Aunan et al., 2004; van Vuuren et al., 2006) and reduced prices of the remaining fossil fuel supplies due to less rapid depletion. In any case, given the current uncertainty range for climate sensitivity and likely ecosystem and ice cap sensitivities, the UNFCCC *requires* that early and stringent emission reductions be undertaken because the UNFCCC is a risk-averse framework as far as impacts on ecosystems, food production, sustainable socio-economic systems and other assets are concerned.

## 3. Summary

This article has addressed the role of the present uncertainty concerning climate sensitivity and the temperature threshold for significant harm. In particular, we revisit the supposed dilemma, posed in earlier work, of whether it is better to (1) risk making early emission reductions that turn out to have been unnecessary (because the climate or ecosystem sensitivity turns out to be smaller than thought at the time of the emission reductions), or (2) risk having to make faster and/or deeper reductions later because initial emission reductions were delayed until uncertainties were reduced. It is shown here that there is no such dilemma, because if stringent emission reductions (sufficient to reduce global $CO_2$ emissions to the 2010 level by 2020) are initiated now, as required under the risk-averse strategy that is enshrined in Article 2 of the UNFCCC, there is almost no plausible combination of true climate sensitivity and harm threshold that would render this unnecessary. For plausible worst (and intermediate) case assumptions, it is not possible to avoid significant harm even with immediate stringent emission reductions. With more optimistic assumptions for climate sensitivity and the harm threshold, the extent of harm is decreased but stringent near-term emission reductions are still required. Only for the unlikely combination of a very low climate sensitivity (1 K) and a high harm threshold (2 K) are no near-term emission restraints required. However, in this case, significant changes in the chemistry of the global oceans would still occur, due to the absorption of the initially unrestrained $CO_2$ that is emitted into the atmosphere.

Thus, irrespective of how current uncertainties are resolved (within the range of outcomes that is considered to be plausible at present), stringent near-term emission constraints will not turn out to be unnecessary from a climatic and/or ocean chemistry point of view. In this sense, the resolution of current scientific uncertainties has no implications concerning near-term GHG emission policy.

## Acknowledgements

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## Note

1 The precise stabilized emission level in reality would depend on the strength of the positive climate-carbon cycle feedback which, as already noted, is weaker in the present model than in some other models, thereby permitting larger emissions.

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