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Dangerous anthropogenic interference, dangerous climatic change, and harmful climatic change: non-trivial distinctions with significant policy implications

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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. However, some of the recent policy literature has focused on dangerous climatic change (DCC) rather than on DAI. DAI is a set of increases in GHGs concentrations that has a non-negligible possibility of provoking changes in climate that in turn have a non-negligible possibility of causing unacceptable harm, including harm to one or more of ecosystems, food production systems, and sustainable socio-economic systems, whereas DCC is a change of climate that has actually occurred or is assumed to occur and that has a non-negligible possibility of causing unacceptable harm. If the goal of climate policy is to prevent DAI, then the determination of allowable GHG concentrations requires three inputs: the probability distribution function (pdf) for climate sensitivity, the pdf for the temperature change at which significant harm occurs, and the allowed probability ("risk") of incurring harm previously deemed to be unacceptable. If the goal of climate policy is to prevent DCC, then one must know what the correct climate sensitivity is (along with the harm pdf and risk tolerance) in order to determine allowable GHG concentrations. DAI from elevated atmospheric CO_2 also arises through its impact on ocean chemistry as the ocean absorbs CO_2. The primary chemical impact is a reduction in the degree of supersaturation of ocean water with respect to calcium carbonate, the structural building material for coral and for calcareous phytoplankton at the base of the marine food chain. Here, the probability of significant harm (in particular, impacts violating the subsidiary conditions in Article 2 of the UNFCCC) is computed as a function of the ratio of total GHG radiative forcing to the radiative forcing for a CO_2 doubling, using two alternative pdfs for climate sensitivity and three alternative pdfs for the harm temperature threshold. The allowable radiative forcing ratio depends on the probability of significant harm that is tolerated, and can be translated into allowable CO_2 concentrations given some assumption concerning the future change in total non-CO_2 GHG radiative forcing. If future non-CO_2 GHG forcing is reduced to half of the present non-CO_2 GHG forcing, then the allowable CO_2 concentration is 290–430 ppmv for a 10%

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risk tolerance (depending on the chosen pdfs) and 300–500 ppmv for a 25% risk tolerance (assuming a pre-industrial CO_2 concentration of 280 ppmv). For future non-CO_2 GHG forcing frozen at the present value, and for a 10% risk threshold, the allowable CO_2 concentration is 257–384 ppmv. The implications of these results are that (1) emissions of GHGs need to be reduced as quickly as possible, not in order to comply with the UNFCCC, but in order to minimize the extent and duration of non-compliance; (2) we do not have the luxury of trading off reductions in emissions of non-CO_2 GHGs against smaller reductions in CO_2 emissions, and (3) preparations should begin soon for the creation of negative CO_2 emissions through the sequestration of biomass carbon.

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 GHG concentrations is one point in a long cause–effect chain that involves emissions of GHGs, increases in concentrations, changes in climate, and impacts.

There has been some discussion in the literature as to which point in this cause–effect chain should be the target of climate policy, and in particular, whether climate policy should directly target greenhouse gas concentrations, or climatic change (Pershing and Tudela 2003; Shine et al. 2005). The two are linked through the climate sensitivity, which is often defined as the longterm, globally-averaged change in temperature associated with a doubling of CO_2 concentration. The climate response to an increase in the concentrations of a mixture of GHGs is roughly proportional to the total heat trapping (radiative forcing) associated with that combination. Thus, the higher the climate sensitivity, the greater the eventual warming for any given increase in concentrations. Several recent papers on this subject (Caldeira et al. 2003; Wigley 2004; Mastrandrea and Schneider 2004; Schneider and Mastrandrea 2005) have focused on dangerous climatic change rather than dangerous interference in the climate system.

The purpose of this paper is three-fold. The first is to show that, although concentrations and climatic change are related through the climate sensitivity, there are important conceptual differences between targeting concentrations rather than climatic change, and these conceptual differences lead to very important differences concerning what the appropriate climate policy is at present. The assessment of what constitutes DAI requires a consideration of climate sensitivity and its uncertainty, the range of possible temperature changes above which unacceptably large negative impacts occur, and also of a morally-acceptable tolerance for risk. This last parameter has not been considered in previous assessments of the range of GHG concentrations that would be consistent with the UNFCCC. Thus, a second purpose of this paper is to present a more complete assessment of the CO_2 concentration limit that complies with Article 2 of the UNFCCC, taking into account all three factors identified above. The identification of a morally-acceptable risk tolerance requires a consideration of the involuntary risks that are considered acceptable in other areas of potential harm or death to others. The key conclusion from this paper is that, for a wide range of assumptions concerning these three inputs, the current (2006) CO_2 concentration of 380 ppmv already violates the UNFCCC.

A third purpose of this paper is to draw attention to the fact that increasing atmospheric GHG concentrations represent 'interference' in the climate system not only through radiative forcing (leading to climatic change), but also through effects on oceanic chemistry.

The absorption of anthropogenic CO_2 by the oceans leads to changes in the pH of the ocean and in its saturation state with respect to calcium carbonate that in turn could eventually have profoundly negative effects on marine biological productivity. Marine biological productivity is an integral part of the climate system, through its effect on the sulfur cycle (through emissions of precursors to dimethyl sulfide), the carbon cycle (through the biological pump), other biogeochemical cycles, and on surface albedo (through enhanced absorption of solar radiation by chlorophyll). These effects are independent of any changes in climate through the radiative forcing of CO_2. A disruption in the biological pump (and possibly also in the sulfur cycle) would act to warm the climate. It could be argued that if the direct climatic effects of CO_2 are small, then feedback effects through changes in ocean chemistry will also be small and so do not constitute dangerous interference in the climate system. However, this is only a speculative possibility at the moment. More importantly, increasing GHG concentrations are 'dangerous' due, ultimately, to their potential adverse impacts, whether or not these impacts involve the intermediate step of climatic change. Thus, it is appropriate to interpret the goal of avoiding dangerous interference in the climate system as a goal of avoiding dangerous interference in the broader Earth system, including both climate and life-support components. Thus, the afore-mentioned literature, by equating dangerous anthropogenic interference with dangerous climatic change and focusing on the latter, omits an important additional realm of dangerous anthropogenic interference in the broader Earth system arising from the increase in atmospheric CO_2.[1]

2 Determining GHG concentrations or radiative forcing that constitutes dangerous anthropogenic interference

I begin by making the following distinctions with regard to impacts on climate:

> *Dangerous anthropogenic interference* (DAI) in the climate system is a set of increases in GHGs concentrations that has a non-negligible possibility of provoking changes in climate that in turn have a non-negligible possibility of causing unacceptable harm to humans, human societies, or natural ecosystems.[2]
> *Dangerous climatic change* is a change of climate that has a non-negligible possibility of causing harm to humans, human societies, or natural ecosystems.
> *Harmful climatic change* is a change in climate that does in fact cause harm to one or more of the above.

Article 2 of the UNFCCC, after declaring that the ultimate objective of the 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, goes on to state that, "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". By

[1] Strictly speaking, it is not the CO_2 concentration (that is, its buildup in the atmosphere) that changes ocean chemistry, but rather, the absorption of CO_2 from the atmosphere by the oceans. However, if CO_2 were to be capped and maintained at a given atmospheric concentration, continuous changes in ocean chemistry would occur, and these changes would be faster and greater the higher the concentration at which atmospheric CO_2 is capped.

[2] The ambiguity associated with the term "non-negligible" will be circumvented later through the presentation of pdfs and the calculation of the probability of harm as a function of radiative forcing, with the reader free to chose whatever probability he or she thinks is too large a risk.

speaking of adaptation to climatic change, it is implied that the ultimate climatic change (related to the chosen GHG stabilization levels) is small enough and hence benign enough that adaptation is possible in the first place. The three subsidiary conditions (allowing ecosystems to adapt, maintaining food production, and enabling sustainable economic development) are restrictions on the *rate* at which non-dangerous greenhouse gas (GHG) concentrations are reached. They are related to that fact that climatic change that is not harmful (that is, sufficiently limited that adaptation is possible), were it to occur slowly, could be highly disruptive (harmful) if it were to occur too fast. These conditions thus set a constraint on rates of allowable GHG emissions, while the overall goal of capping GHG concentrations at non-dangerous levels largely represents a constraint on cumulative CO_2 emissions. In the following discussion of DAI, however, we will focus on the risks associated with different alternative longterm concentration limits.

Increases in GHG concentrations alter climate through their radiative forcing, and it is the total radiative forcing rather than the specific combination of GHGs that matters for climate (to within about 10% error). Thus, calling for stabilization of GHGs concentrations is equivalent to calling for stabilization of total GHG radiative forcing. Thus, in the reminder of this discussion, I shall normally refer to radiative forcing rather than GHGs concentrations.

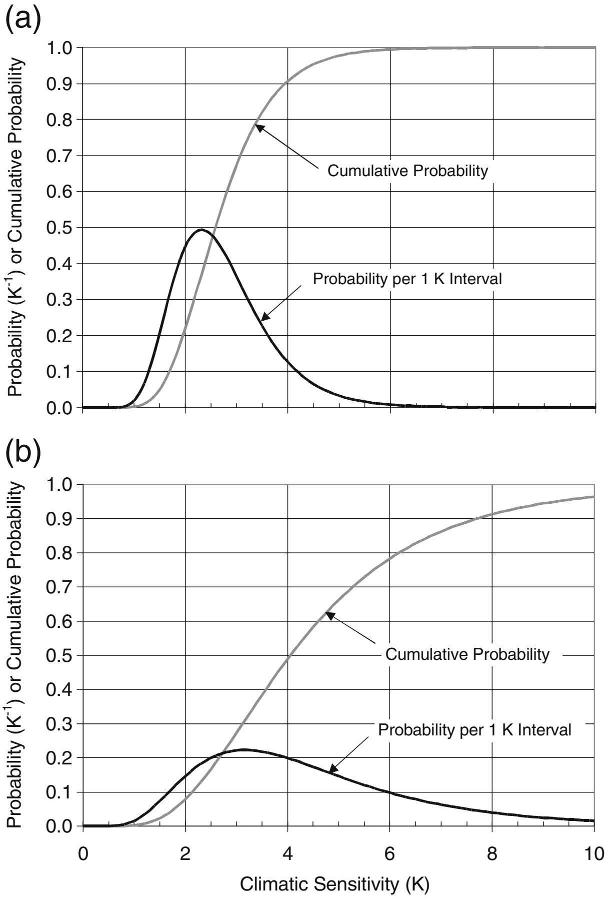
In order to determine an allowable radiative forcing, one needs to (1) specify a probability distribution function (pdf) for climate sensitivity, (2) specify the probability of harmful impacts as a function of the amount of climatic change, and (3) specify the risk tolerance. Previous work in assessing DAI has focused almost exclusively on the first two factors, with only Wigley (2004) making passing reference to the risk tolerance.

Here, I will discuss alternative estimates of each of the three inputs needed to assess DAI through radiative forcing (climate sensitivity pdf, harm pdf, and risk tolerance), and illustrate their interaction. As noted in the introduction, an increasing CO_2 concentration constitutes interference in the climate system through changes in ocean chemistry as well as through radiative forcing. Although the ocean chemical effects depend on the cumulative absorption of CO_2 by the oceans, it is possible to associate specific changes in ocean chemistry over a given time frame with cumulative anthropogenic emissions and with the atmospheric CO_2 concentration reached over that time frame. This provides a direct link between CO_2 concentration and harm that does not depend on temperature changes and therefore does not require climate sensitivity and temperature-based harm pdfs. Possible implications for allowable CO_2 concentrations are also discussed here.

2.1 Probability distribution functions for climate sensitivity

Figure 1 shows two different pdfs for the climate sensitivity. The first is a subjective pdf that agrees with the consensus viewpoint. The longstanding consensus (going back to the late 1970s) is that the climate sensitivity is 'likely' to fall between 1.5 and 4.5 K, although 'likelihood' has never been rigorously defined. However, there are several independent lines of evidence that all indicate that the climate sensitivity is likely to fall somewhere within this window: simulations with 16 atmospheric GCMs, which span a sensitivity range of 2.0–5.1 K (Cubasch et al. 2001), analysis of warm and cold climates in the geological past, which suggest a sensitivity of 1.4–3.2 K (Hoffert and Covey 1992); analysis of the observed warming during the past 150 years in combination with estimates of the total radiative forcing, which suggest a likely sensitivity of 2–4 K (e.g., Harvey and Kaufmann 2002), and analysis of the short term response to the eruption of Mt. Pinatubo in 1991, which also suggests a likely sensitivity of 2–4 K (Wigley et al. 2005). Most analyses

Fig. 1 The two probability density functions for climate sensitivity considered here, and the corresponding cumulative pdfs. **a** low pdf (μ=0.95 and σ=0.33), **b** high pdf (μ=1.4 and σ=0.5)



produce a climate sensitivity probability distribution that is skewed, with a longer tail on the high-probability side than on the low-probability side. A skewed shape can be obtained by assuming a lognormal distribution (as in Wigley and Raper 2001; Wigley 2004) and, based on the evidence cited above, I subjectively assume that the probability of the climate sensitivity being less than 1.5 K or greater than 4.5 K is about 5% in each case. A lognormal pdf is characterized by the mean of the logarithm (μ) and by the standard deviation of the logarithm (σ). The pdf and the cumulative pdf are given in Fig. 1a for μ=0.95 and σ=0.33. This distribution has a mode of 2.5 K and a mean of 2.74 K, compared to a mode of about 3.0 K and a mean of 3.47 K for the 16 AGCM sensitivities reported by Cubasch et al. (2001).

Independent evidence concerning climate sensitivity can be obtained from the simulation of atmospheric CO_2 variations over the past 600 million years. The atmospheric CO_2 concentration varied over this time interval in response to imbalances between volcanic outgasing and changing rates of weathering due to variations in plate tectonic activity and associated mountain uplift, but the magnitude of the CO_2 variation depends on how strong the negative feedback is between CO_2 concentration and removal rates by chemical weathering. This in turn depends on how large the climate sensitivity is (warmer temperatures drive higher weathering rates). If climate sensitivity is too small (less than about 1.5 K), impossibly high

CO_2 peaks are obtained, while if it is too large (greater than about 3 K), unreasonably low Mesozoic values are obtained (Berner 2004, pp. 80–83, and Berner, personal communication, 2006). These must be regarded as very rough limits on climate sensitivity.

Some workers have attempted to generate ‘objective’ pdfs for climate sensitivity. One approach involves separating externally-forced climatic variations from short-term internally-generated climate variability in the 150-year observational record, generating 1,000s of alternative realizations of internal variability, determining the climate sensitivity that gives the best match between model-simulated climatic change and alternative ‘observed’ climatic change for each of the alternative realizations of internal variability, and computing the pdf of the best-fit climate sensitivities (Andronova and Schlesinger 2001). The resulting pdf is dependent on how externally-forced climatic is separated from internally-generated variability, and whether or not longterm internal variability is included along with short-term internal variability in generating alternative realizations of internal variability. Andronova and Schlesinger (2001) generated three different pdfs, corresponding to three different sets of assumptions concerning the forced variability that is present in the observational record. A composite pdf that combines all three cases yields a 5%–95% cumulative probability range of 1.0–9.3 K. As discussed in Harvey and Kaufmann (2002), Andronova and Schlesinger (2001) may have assigned too much of the observed climate variability to short-term internally-generated variability, thereby possibly generating unrealistically high probabilities of very high climate sensitivities.

Gregory et al. (2002) estimated a pdf for climate sensitivity by computing the climate sensitivity required to match the observed warming between the periods 1861 and 1900 and 1957 and 1994 for various combinations of the estimated observed warming, oceanic uptake of heat, and anthropogenic and natural radiative forcing. For any given calculation, values for each of the inputs were selected from assumed pdfs for the input values. By using a pdf of observed warming rather than a single observed warming, alternative possible realizations of internal climate variability are implicitly allowed. The resulting climate sensitivity pdf gives a 50% probability of a climate sensitivity of 6.1 K or greater.

Knutti et al. (2002) and Forest et al. (2002, 2006) derived pdfs based on the frequency distribution of climate sensitivities such that the model simulated global mean temperature variation falls within some envelope of the observed temperature variation. A range of values for aerosol radiative forcing and oceanic uptake of heat was considered. They derived 5%–95% cumulative probability ranges of 1.7–8.6 K and 2.1–8.9 K, respectively. Alternatively, Hegerl et al. (2006) derived a climate sensitivity pdf based on comparison of model-simulated and reconstructed (from proxy data) temperature variations from A.D. 1000 to the present. They obtain a 5%–95% probability range of 1.5–6.2 K. Pdfs of climate sensitivity have also been derived by systematically varying a large number of parameters within one particular climate model. Murphy et al. (2004) obtained a 5%–95% probability range of 2.5–5.4 K, while Piani et al. (2005) obtained a 5%–95% probability range of 2.2–6.8 K using this approach.

The statistical generation of pdfs in the papers by Knutti et al. (2002), Forest et al. (2002, 2006), and Hegerl et al. (2006) requires making some initial explicit assumption concerning the distribution of climate sensitivity and the limits of the distribution. The climate sensitivity (ΔT_{2x}) depends on the feedback factor (f) according to

$$\Delta T_{2x} = \frac{(\Delta T_{2x})_o}{1-f} \tag{1}$$

where $(\Delta T_{2x})_o$ is the temperature response to a CO_2 doubling in the absence of feedbacks except for the that given by the increase of blackbody emission with temperature [$(\Delta T_{2x})_o$=1.0 K]

(Harvey 2000, Chapter 3). As discussed by Frame et al. (2005), uniform sampling in f generates a pdf for ΔT_{2x} that is highly skewed, with many values concentrated toward low sensitivity and a long tail of low probabilities extending toward high sensitivity, while uniform sampling in ΔT_{2x} (as in the work by Knutti, Forest, and Hegerl, cited above) generates a pdf shifted toward higher climate sensitivities. The approach taken by Murphy et al. (2004), in which model simulations are performed with parameter values selected from an assumed uniform distribution of values, is equivalent to uniform sampling in f and so, not surprisingly, generates a pdf that is shifted toward lower sensitivities. Thus, the final results in all these cases depend in part on arbitrary prior assumptions.

Nevertheless, an alternative pdf (shown in Fig. 1b) will be considered here (using μ= 1.4 and σ=0.5) that generates a 5%–95% interval of 1.8–9.2 K and a 20% probability of a climate sensitivity of 6.0 K or greater. This pdf is shifted slightly more strongly to higher climate sensitivities than that of Knutti et al. (2002), is comparable to that of Andronova and Schlesinger (2001) and Forest et al. (2006), but is less extreme than that of Gregory et al. (2002). Although Hoffert and Covey's (1992) analysis of paleoclimatic data suggested a sensitivity of only 1.4–3.2 K, a more recent analysis by Lea (2004) indicates a sensitivity of tropical sea surface temperatures of 4.4–5.6 K. Inasmuch as tropical regions are normally less sensitive than the global mean temperature, this result also suggests a pdf shifted toward higher sensitivities than the 1.5–4.5 K 90% probability range shown in Fig. 1a.

2.2 Probability of harm as a function of global mean temperature change

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. Some ecosystems and food production systems are quite sensitive to climatic change, while others are more resilient. Furthermore, there is considerable uncertainty as to where the critical thresholds of temperature change lie for different ecosystems and food production systems. The critical temperature thresholds will depend in some cases on the concurrent changes in the amount, timing, and nature of seasonal precipitation; on the possibilities for adaptation of both natural and human systems; and also on the extent to which previous human disturbances increase the vulnerability of natural ecosystems to climatic change. Despite these uncertainties, it is possible, given current knowledge, to estimate likely lower and upper limits for the thresholds of temperature change, beyond which significant harm occurs for a number of different impact areas. Four impact areas are selected for discussion here: coral reef ecosystems, sea level rise, vulnerable socio-economic and food-producing systems, and terrestrial ecosystems and forests. For a comprehensive discussion of potential impacts at various global mean warmings, see Warren (2006).

2.2.1 Coral reef ecosystems

Coral reefs are a great storehouse of biodiversity, housing about 100,000 species that have been described and an estimated total of 0.5–2.0 million species (Reaka-Kudla 1996). They provide direct sustenance to an estimated 100 million people, with additional benefits to local societies through tourism revenues (Hoegh-Guldberg 2005). They are particularly sensitive to temperature increases, will be adversely affected by decreasing carbonate supersaturation, and may not be able to keep up with rising sea level. Here, we discuss temperature impacts, while sea level rise and changing carbonate supersaturation are discussed later.

Coral organisms live in a symbiotic relationship with a photosynthetic organism, and grow in ocean waters ranging from 26°C to 34°C in temperature. When water temperatures increase by only 1 K beyond the normal peak seasonal temperature in a given region, the symbiont is expelled, causing the coral to lose colour. Prolonged expulsion of the symbiont leads to the eventual death of the coral. Seasonal temperature peaks in tropical regions generally occur during El Niño years. The most severe El Niño to date occurred in 1998, when 16% of the world's coral reefs experienced severe bleaching, in some cases killing corals that were 1,000 years old (Goldberg and Wilkinson 2004). The decadal global mean temperature was about 0.6 K warmer than that of the late 1800s/early 1900s at this time, with 1998 being about 0.9 K warmer than the late 1800s/early 1900s mean. As longterm average temperatures increase, future El Niño peaks will be progressively warmer, leading to more severe and more frequent beaching events. In the Indian Ocean, more than 90% of shallow corals were killed by the 1998 El Niño, and an event of this magnitude is expected one year in five by the mid 2020s (Sheppard 2003). Donner et al. (2005) have assessed the impact of climatic change as projected by two different AOGCMs for the frequency and severity of coral bleaching. They find that severe bleaching occurs at the majority of the world's coral reefs in the 2030s and becomes a biannual event by the 2050s, by which time global mean temperature has increased by about 2 K above that of the late 1800s in the AOGCMs under consideration.

Adaptation could delay the regular occurrence of severe bleaching. The large range of temperatures at which coral reefs grow today implies that there is some genetically-based diversity in the temperature tolerance of the symbionts. Warmer temperatures would favour organisms with a greater tolerance of heat, leading to a shift in the composition of reef symbiont populations toward tolerance of warmer temperatures. The critical issues concern (1) the rate at which such shifts can occur, (2) the temperature limits of adaptation, and (3) the occurrence of adverse tradeoffs in other areas (such as productivity) in exchange for greater temperature tolerance. Although there may be a substantial genetic ability for adaptation to warmer temperature, natural rates of adaptation are likely to be quite slow and will be further inhibited by other stresses on coral reefs, including reduced carbonate supersaturation in surface waters (Hughes et al. 2003; Hoegh-Guldberg 2005). More temperature-tolerant symbionts are observed to have slower and less vigorous growth, because of the energetic cost of enhanced protective machinery (Donner et al. 2005). This in turn would limit the reef's ability to keep up with rising sea level or to deal with other stresses (such as nutrient loading, sedimentation, and disease). With adaptation, it is conceivable that significant and widespread harm could be delayed until global mean temperatures exceed 2 K. Thus, it seems reasonable to assume that the likely threshold for significant harm to coral reefs occurs somewhere between global mean temperature changes of 1 and 2 K.

2.2.2 Sea level rise

With regard to sea level rise (SLR), the critical processes include the melting of the Greenland ice sheet (GIS) and the destabilization and collapse of the West Antarctic ice sheet (WAIS). There are two critical issues here: (1) the temperature thresholds at which the irreversible melting of the GIS and the collapse of the WAIS could be provoked, and (2) the rate of collapse (and associated SLR). Either event would raise sea level by about 5–6 m. Two competing effects would be at work as the climate of Greenland warms: an increase in the rate of precipitation on the one hand, and an increase in the rate of melting and the fraction of precipitation falling as snow on the other hand. Computer simulations by Huybrechts and de Wolde (1999) indicate that a net loss would occur with a regional warming of about 3 K, and that an 8 K warming would cause near-total melting by A.D. 3000. These results were obtained assuming an annually uniform warming. The GIS is likely most sensitive to summer temperatures, and summer warming is likely to be less than the annual mean warming. This in turn implies that the required mean annual warming is somewhat greater than 3 K (given the various uncertain parameterizations in the Huybrechts and de Wolde model). It is unclear what global mean warming would be associated with a given regional warming over Greenland. In some coupled atmosphere–ocean GCMs the regional warming over Greenland is much more than the global mean warming, while in others it is comparable to the global mean warming (the normally large high latitude warming being reduced in the North Atlantic sector due to changes in the North Atlantic current) (Harvey 2004b). Thus, there is considerable uncertainty concerning the global mean temperature change large enough to initiate collapse of the GIS, but seems likely to fall in the 2–4 K range. Irreversible melting of the GIS would occur when initial melting of the ice cap lowers (and therefore warms) the surface elevation to the point that melting would continue even if GHG concentrations were to return to some lower level. The WAIS is grounded on sills below sea level and is susceptible to collapse once the ocean water surrounding it begins to warm and weakens the grounding points. Regional warming of 4–8 K may be sufficient to destabilize the WAIS, although the risk is poorly quantified (Oppenheimer and Alley 2004).

Geological data indicate that collapse of the GIS or WAIS in association with modest warming is a very real risk. Sea level was likely 4–6 m higher during part of the previous interglacial period (130,000 to 127,000 years ago) but global mean temperature was only about 1 K warmer (Stirling et al. 1998; Cuffey and Marshall 2000; McCulloch and Esat 2000; Overpeck et al. 2006). Simulations with a state-of-the-art coupled ice sheet atmosphere–ocean climate model of conditions during the last interglacial indicate that summer temperatures along the coast of Greenland were about 3 K warmer than at present, and were sufficient to provoke partial but not complete melting of the GIS (Otto-Bliesner et al. 2006). The last-interglacial simulations of Otto-Bliesner et al. (2006) reproduce many patterns of the last interglacial climate, inferred from paleoclimatic evidence, including the lack of warming in the southern hemisphere. The simulated partial melting of the GIS contributes 2.2–3.4 m sea level rise; however, the Greenland ice cap will likely be more susceptible to future melting than during the last interglacial, due to the reduction in snow albedo from anthropogenic soot. Some contribution to the last interglacial sea level peak from the West Antarctic ice sheet or from the margins of the East Antarctic ice sheet is implied, likely induced by the initial sea level rise from partial melting of the Greenland ice cap. During the middle Pliocene (3 million years ago), global mean temperatures are estimated to have been 3 K warmer than today (Crowley 1996; Dowsett et al. 1996) and sea level 25±10 m higher than today (Barrett et al. 1992; Dowsett et al. 1994; Dwyer et al. 1995). This suggests that the threshold for a mere 5–6 m sea level rise is less than 3 K global mean warming.

Conventional thinking is that very little change will occur in the Greenland and Antarctic ice sheets during the next century, such that, in combination with thermal expansion of ocean water and melting of alpine glaciers, average sea level will rise by only 9–88 cm during the period 1990–2100 (Church et al. 2001). Indeed, may models predict that Antarctica will grow in mass as the climate warms, due to increased snowfall, thereby contributing to a fall in sea level. However, in order to reconcile the observed SLR of about 20 cm during the past century with estimated SLR due to the sum of all contributing processes, it must be assumed that Antarctica has contributed a SLR of about 10 cm during the past century – that is, that the Antarctic ice cap is currently losing mass (Harvey 2000, Chapter 5). Current ice sheet models do not include processes such as infiltration of surface meltwater through crevices to the ice sheet bed, where it can lubricate the bed and lead to accelerated flow (Alley et al. 2005). During the last deglaciation, sea level rose as rapidly as 20 m per 400 years – a rate of increase that current models cannot simulate. Hansen (2005) has raised the possibility that SLR due to melting of the Greenland ice cap and collapse of the West Antarctic ice sheet could be much more rapid that currently believed. Rapid collapse of Greenland could begin through lubrication of the base of the ice cap from meltwater due to a single unusually warm summer, perhaps in combination with summer rainfall, which could lead to significant discharge of ice into the North Atlantic ocean, where heat from a large volume of ocean water could be used to melt the ice at much greater rates than could occur *in situ*. Such events occurred repeatedly during the last ice age. As noted by Oppenheimer and Alley (2005), computer models of the WAIS may also be too resistant to warming, as they do not simulate ice streams well.

Based on the above, it is concluded here that an increase in global mean temperature of somewhere between 1 and 3 K will likely destabilize either the Greenland ice cap or the West Antarctic ice cap or both.

2.2.3 Threats to food production, water supplies, and sustainable socio-economic systems

It is increasingly recognized that a global mean warming poses a great risk to sustainable development in many ways, by undermining agricultural and forest productivity, reducing water supplies and water quality, and endangering productive coastal marine ecosystems (Beg et al. 2002; Swart et al. 2003; Munasinghe and Swart 2005). Estimates of the number of people at risk from water shortages by Parry et al. (2001), as a function of global average warming, show an abrupt increase between 1 and 2 K global mean warming, with a more gradual increase in other risks (flooding, malaria, hunger). Barnett et al. (2005) review potential impacts of global warming on water supplies in regions dependent on melting of winter snow cover and on glacier meltwater. Currently, more than one sixth of the world's population is dependent on such water sources, including one quarter of China's population. Serious water shortages are likely to arise in such regions within a few decades. Warming and precipitation changes due to anthropogenic climatic change may already be claiming 150,000 lives annually, with the prospect of a significantly greater toll in the future, especially in regions with many climate-sensitive diseases such as Africa (Patz et al. 2005). Assessments of the impact of a doubled-CO_2 climate (2–5 K global mean warming) frequently show decreases in agricultural yields in specific regions of 10%–30% and more, even after allowing for the beneficial physiological effects of higher CO_2 and for adaptation (see Gitay et al. 2001, Table 5.4; Parry et al. 2004). Overall, a threshold for significant harm between 1 and 2 K global mean warming is implied.

2.2.4 Threats to terrestrial ecosystems and forests

Leemans and Eickhout (2004) performed a global scale assessment of the impact of 1, 2, and 3 K warming on terrestrial ecosystems, using a series of computer simulation models. Their simulations indicate that a 1–K global mean warming will cause changes in the type of ecosystem over about 10% of the Earth's land surface, increasing to about 22% for a 3–K global mean warming. However, even at 1 K warming over a period of a century, only 36% of impacted forests can shift in step with the climatic change (that is, 'adapt'), due to their long generation times and relatively slow rate of dispersal. At 3 K warming by 2100, only 17% of impacted forests can keep up. Thus, even a 1–K warming over a period of 100 years (0.1 K/decade) can be regarded as dangerous climatic change, in that many terrestrial ecosystems are not likely to be able to adapt naturally to the changing climate.

A global mean warming of 3–4 K over the course of the next century could have highly disruptive effects on tropical forest ecosystems (Arnell et al. 2002). Of particular concern are simulations by the HadCM3 atmosphere–ocean model at the Hadley Centre in the UK, in which almost the entire Amazon rainforest is replaced by desert by the 2080s due to a drastic reduction in rainfall in the Amazon basin in association with a global mean warming of about 3.3 K (White et al. 1999; Cox et al. 2004). In the HadCM2 model (an earlier version of the Hadley Centre model), the Amazon rainforest is still largely intact by 2100 (when the simulation ends) but with greatly reduced productivity, and a positive climate–carbon cycle feedback results in an atmospheric CO_2 concentration in 2100 of 1,000 ppmv for an emission scenario that otherwise would have led to 750 ppmv by 2100 (Cox et al. 2000). Non-climatic human disturbances of tropical forests are increasing, and disturbed forests are particularly vulnerable to drought, as logging removes deep-rooted trees, edges around cleared areas are subject to drying, and the pastures in logged areas are burned regularly and thus serve as a fire hazard to the remaining forest (Laurance and Williamson 2001). This further increases the vulnerability of tropical forests to climatic change.

A group of 19 ecologists from five continents (Thomas et al. 2004) has recently assessed the impact of projected future climatic change on the rate of extinction of terrestrial animal species.[3] Species loss was estimated based on empirical relationships between habitat area and the number of species, using three different approaches that give similar answers. Temperature changes for 2050 as obtained by the HadCM2 model for a variety of different emission scenarios were used as input, with two limiting assumptions concerning plant and animal species: (1) uninhibited dispersal, and (2) no dispersal. The case of no dispersal represents the impact of habitat fragmentation and human barriers; reality will fall somewhere between the full-dispersal and no-dispersal cases. Table 1 summarizes the percent of animal species committed to extinction by 2050 for three sets of scenarios and the two limiting cases (published temperature changes are with respect to the 1961–1990 mean, and have been increased here by 0.3 K in order to be relative to the late 1800s). For scenarios in which the global mean warming reaches 2.1–2.3 K by 2050, between one sixth and one third of land animal species will be committed to extinction – that is, although not yet extinct, will have passed the point of no return in terms of habitat loss and its implications for survival. Similar losses averaged over 25 biodiversity hotspots and in association with a CO_2 doubling were independently obtained by Malcolm et al. (2006). There is growing evidence that some species have already been pushed to or close to extinction by recent warming (Pounds et al. 2006; Blaustein and Dobson 2006). Not included in either assessment are possible synergistic interactions between climatic change and other factors (such as further reductions in habitat area due to land use changes or the impact of new invasive species on ecosystems already stressed by climatic change). Inasmuch as a loss of one sixth to one third of terrestrial land species is unacceptable, the slightly more than 2 K warming associated with this outcome can be regarded as too much. Thus, we again come to the conclusion that an allowable warming for ecosystems is well below 2 K, likely around 1 K or less (depending on how much species loss is accepted).

[3] See also the exchange of viewpoints in *Nature*, Vol. 427, pp. 145–8.

Table 1 Fraction of terrestrial animal species estimated by Thomas et al. (2004) to be committed to extinction by 2050 for GHG emission scenarios producing different amounts of global mean warming by 2050, assuming uninhibited dispersal or no dispersal

	Change in global mean temperature		
	1.1–2.0 K	2.1–2.3 K	2.9–3.3 K
With dispersal (%)	9–13	15–20	21–32
Without dispersal (%)	22–31	26–37	38–52

2.2.5 Synthesis: probability of harm as a function of global mean temperature change

It has been noted (Schneider and Mastrandrea 2005) that policy makers may focus on specific criteria (such as harm to ecosystems, food production, market impacts, quality of life) in defining DAI, and are likely to disagree as to which criteria should be used, and that different countries may focus on risks in different regions of the world (presumably their own) in defining DAI. However, inasmuch as Article 2 of the UNFCCC calls for protection of ecosystems *and* food production *and* sustainable socio-economic systems, it is reasonable to conclude that DAI should be defined in terms of the most vulnerable of the three. That is, DAI arises from GHG concentrations that pose a risk to any one of these three systems. Furthermore, ethical considerations (namely, not harming others) combined with the fact that we live in an interconnected world implies that a common definition of DAI, based on risks to any significant human population or ecosystem, is called for. This is consistent with Article 3 of the UNFCCC, which states that, “The parties should protect the climate system for the benefit of present and future generations of humankind...in accordance with their common but differentiated responsibilities”.

Based on these considerations and the evidence summarized in the preceding sections, I conclude that it is highly likely that the threshold for significant harm lies at a global mean temperature change somewhere between 1 and 2 K. Figure 2a gives a lognormal pdf for the harm threshold, and the cumulative probability distribution function, for μ=0.45 and σ=0.35. These parameter values give a 10% probability that the harm threshold is less than 1 K and a 20% probability that the harm threshold is greater than 2 K, with a most likely threshold of 1.4 K. In order to demonstrate the robustness of the conclusions that will come later, two alternative harm pdfs are also shown in Fig. 2: one (in Fig. 2b, with μ=1.0 and σ=0.3) such that the most likely threshold is a warming of 2.5 K, with a 10% chance that the harm threshold lies at 4 K or greater, and another (in Fig. 2c, with μ=1.25 and σ=0.3) such that the most likely threshold is a warming of 3.2 K, with a 33% chance that the harm threshold lies at 4 K or greater.

2.3 Probability of harm as a function of radiative forcing

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 is assumed that the eventual global mean temperature change varies linearly with the 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 re-organization of the ocean circulation.

Let $PDF_{2x}(\Delta T)$ be the pdf for climate sensitivity – that is, the pdf of longterm temperature change ΔT associated with the radiative forcing of a CO_2 doubling. Then

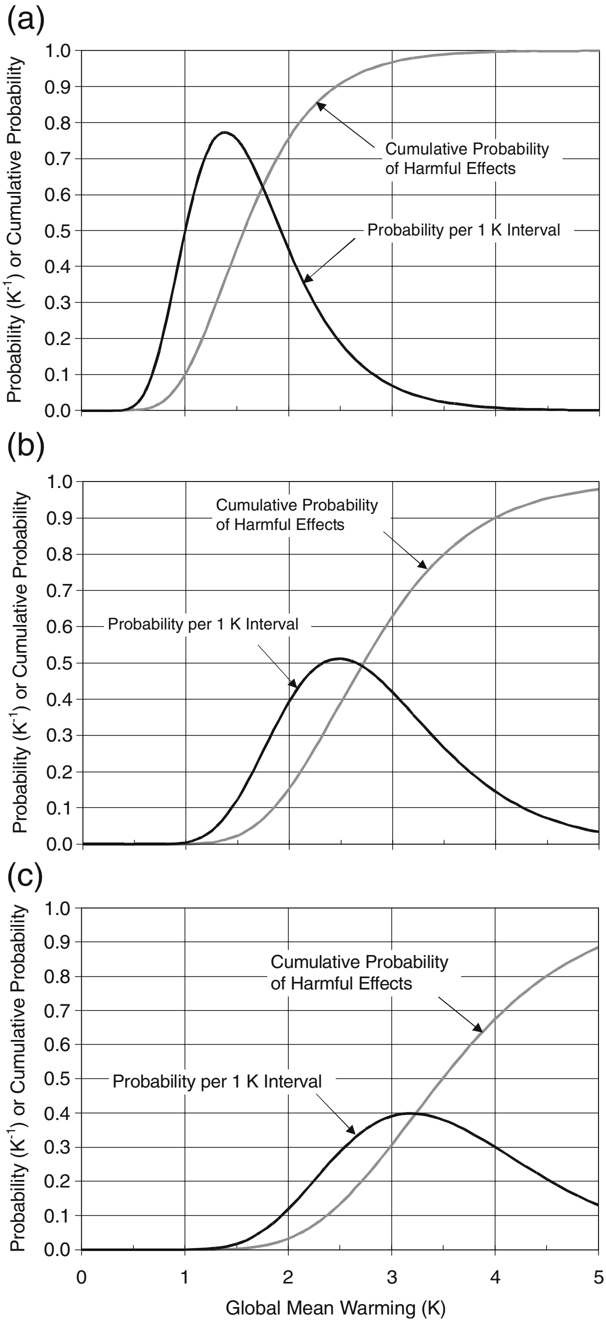


Fig. 2 The three probability density functions considered here for the temperature change beyond which unacceptable harm to one or more of ecosystems, food production, and sustainable-socio-economic systems occurs, and the corresponding cumulative pdfs. **a** Stringent (μ=0.45 and σ=0.35), **b** Moderate (μ=1.0 and σ=0.3), and **c** Loose (μ=1.25 and σ=0.3)

$\Delta(\Delta T_i)PDF_{2x}(\Delta T_i)$ is the probability of the climate sensitivity occurring within an interval of width $\Delta(\Delta T_i)$ centered at ΔT_i. If the radiative forcing is R_f times that for a CO_2 doubling, then $\Delta(\Delta T_i)PDF_{2x}(\Delta T_i)$ is the probability that the temperature change produced by this forcing lies in an interval of width $R_f\Delta(\Delta T_i)$ centered at $R_f\Delta T_i$. Let $CPDF_{harm}(\Delta T_i)$ 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, $\Delta(\Delta T_i)\mathrm{PDF}_{2x}(\Delta T_i)$ $\mathrm{CPDF}_{\mathrm{harm}}(R_f\Delta T_i)$ 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,

$$\begin{aligned} P_{\mathrm{harm}}(R_f) &= \int_0^\infty \mathrm{PDF}_{2x}(\Delta T)\cdot \mathrm{CPDF}_{\mathrm{harm}}(R_f\Delta T)\mathrm{d}\Delta T \\ &= \int_0^\infty \mathrm{PDF}_{2x}(\Delta T)\left(\int_0^{R_f\Delta T} \mathrm{PDF}_{\mathrm{harm}}(\Delta T')\mathrm{d}\Delta T'\right)\mathrm{d}\Delta T \end{aligned} \tag{2}$$

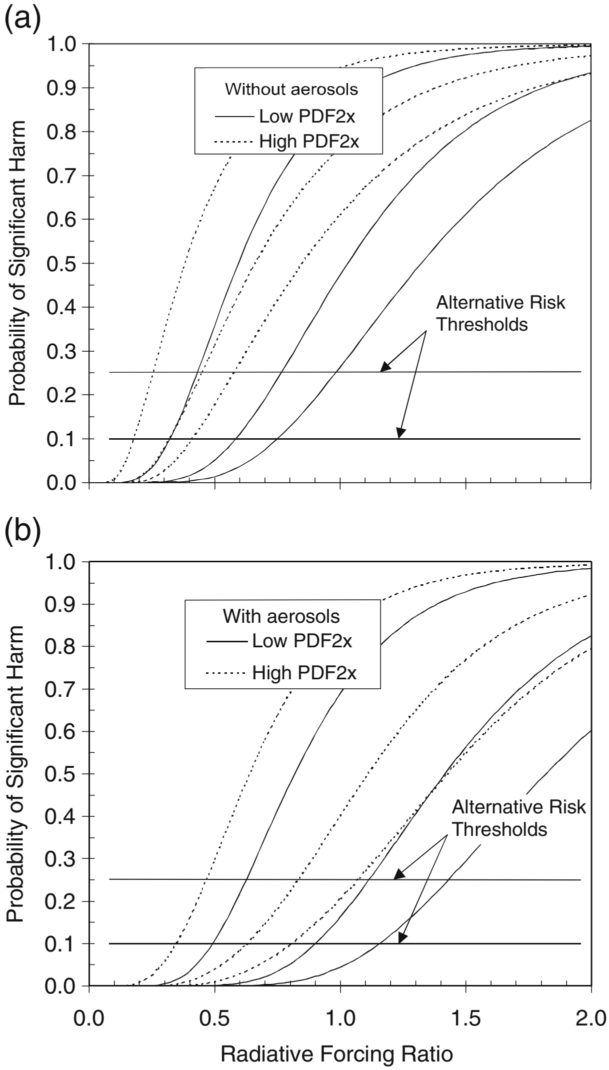
Figure 3a shows $P_{\mathrm{harm}}(R_f)$ for all six combinations of the two pdfs for climate sensitivity and the three pdfs for the temperature threshold for significant harm (Fig. 3b is an alternative estimate of the risk of harm that takes into account the aerosol offset of GHG forcing, and will be discussed later). For any given combination of pdfs, the risk of harm increases with increasing forcing ratio R_f. Thus, in deciding on an acceptable forcing, a third input has to be specified, namely, the acceptable probability of harm of the magnitude used to derive the harm pdf, or more simply, the *tolerance for risk*.

2.4 Acceptable probabilities of harm and implications for the allowable CO_2 concentration

There has been relatively little discussion of acceptable probabilities for significant harm due to global warming. Inasmuch as the risks under consideration involve 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. As for how low, Tonn (2003) suggests three different acceptable probabilities for three different categories of impacts: one in a million for substantial regional economic, political, and/or biological impacts, one in one hundred million for severe global economic, political, and/or biological impacts, and one in ten billion for extinction of humans. The impacts discussed above would fall in Tonn's first category, and Tonn bases his one-in-a-million threshold for this category on the rule of thumb used by the Environmental Protection Agency (EPA) and the Nuclear Regulatory Commission (NRC) in the US, such that individuals should not be involuntarily subjected to a risk of death with a chance greater than one in a million. The choice of risk tolerance is fundamentally a *moral judgment* 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).

The acceptable risk depends in part on the cost (or perceived cost) of reducing the risk. It is also depends on society's ability to pay to reduce the risk. The issue of cost and ability to pay is a complex issue, dependent on a large number of assumptions concerning social structure, public attitudes, political priorities, lifestyle, education and training, and technological development. Although there is a vast literature indicating that large emission reductions can be achieved over a period of a few decades at very little cost (e.g., Brown et al. 1998; Nadel and Geller 2001; Azar and Schneider 2002; Hanson and Laitner 2004; Gerlagh and van der Zwaan 2004; Barker et al. 2006), it may very well be that adopting the risk tolerance used in regulating potentially harmful chemicals or nuclear energy is too stringent when applied to the hazards of increasing GHG concentrations.

Fig. 3 The probability of unacceptable harm, as a function of the radiative forcing ratio, for various combinations of PDF_{2x} and PDF_{harm}. The *three solid curves* are for the low PDF_{2x} and, from *left to right*, the Stringent, Moderate, and Loose PDF_{harm}, while the *three dashed curves* are for the high PDF_{2x} with the same sequence of PDF_{harm}. **a** Neglecting the offset of radiative forcing by aerosols. **b** Taking into account the correlation between climate sensitivity and present-day aerosol radiative forcing that is required in order to replicate the observed warming



Here, the implications for allowable GHG radiative forcing of using two different probabilities of harm will be considered: 10% and 25%. 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), then the average risk of death for any one person is roughly one in one thousand to one in one hundred. Thus, a probability of harm of 10% would correspond to a risk of death to individuals of 1:10,000 to 1:1,000. Thus, in adopting a 10% risk tolerance, we are allowing for a risk of death to individuals that is 100- to 1000-fold greater than the one-in-one-million threshold adopted by the US EPA and NRC. This addresses the possibility that the cost of reducing GHG emissions relative to the cost of eliminating unsafe chemicals or enhancing nuclear safety might imply a higher risk tolerance. For the most vulnerable regions, and especially for the most vulnerable people in these regions, the risks are greater still. The 25% threshold considered here is particularly reckless but is chosen because, as will be seen, it still requires immediate and deep reductions in CO_2 emissions.

The 10% and 25% probabilities are used here as the threshold for ‘danger’, which is to be avoided under Article 2 of the UNFCCC. They are given by the lower and upper horizontal lines, respectively, in Fig. 3a. The intersection of these curves with the probability-of-harm curves gives the allowable radiative forcing ratios R_f. Allowable R_fs are given in Table 2 for the six combinations of PDF_{2x} and PDF_{harm} and the two risk thresholds. For a 10% risk threshold and PDF_{2x} tilted toward low sensitivities (Fig. 1a), allowable R_fs range from 0.33 to 0.77, while for PDF_{2x} tilted toward high sensitivity (Fig. 1b), allowable R_fs range from 0.19 to 0.43. Also given in Table 2 are the allowable CO_2 concentrations assuming, as a limiting case, that the radiative forcing of all non-CO_2 GHGs is reduced to zero, and assuming that the radiative forcing by non-CO_2 GHGs can be reduced by 50% or is frozen at the current value (in computing the allowable CO_2 concentrations, it is assumed that the forcing for a CO_2 doubling is 3.71 W/m^2, that current non-CO_2 GHG forcing is 1.15 W/m^2, that the CO_2 forcing varies with the natural logarithm of the ratio of CO_2 concentration to the pre-industrial concentration, and that the pre-industrial concentration was 280 ppmv). For the intermediate case, where non-CO_2 GHG forcing is reduced in half, the allowable CO_2 concentration ranges from 287–428 ppmv at a 10% risk threshold, and from 300–498 ppmv at a 25% risk threshold.

Thus, assuming stringent reductions in non-CO_2 GHG forcing, compliance with the stated goal of the UNFCCC to prevent dangerous anthropogenic interference in the climate system requires limiting the atmospheric CO_2 concentration to no more than about 430 ppmv even if recent estimates of the PDF_{2x} that are tilted toward high sensitivities are rejected, and even if a highly optimistic PDF_{harm} is adopted. If one considers ‘danger’ to require a risk of significant harm as high as 25%, the allowable CO_2 concentration is still only 498 ppmv under the most favorable combination of PDF_{2x} and PDF_{harm} considered here, and is much less for other combinations of PDF_{2x} and PDF_{harm}.

2.5 What about aerosols?

Increases in the atmospheric loading of non-absorbing aerosols (sulphate, nitrate, organic carbon, soil dust) due to either human emissions of aerosol precursors or human disturbance

Table 2 Allowable GHG radiative forcing (relative to that for a CO_2 doubling) and allowable CO_2 concentration, given alternative pdfs for climate sensitivity and the threshold for harm, and given either 10% or 25% risk tolerance

PDF_{2x}	PDF_{harm}	Allowable GHG radiative forcing ratio (R_f)		Allowable CO_2 concentration (ppmv) if future non-CO_2 GHG forcing is frozen at					
				Zero		Half-present		Present	
		10%	25%	10%	25%	10%	25%	10%	25%
Low	Stringent	0.327	0.433	351	378	315	339	283	305
Low	Moderate	0.597	0.767	424	476	381	428	342	384
Low	Loose	0.766	0.985	476	554	428	498	384	447
High	Stringent	0.189	0.256	319	334	287	300	257	270
High	Moderate	0.331	0.454	352	384	316	344	284	309
High	Loose	0.425	0.583	376	420	338	303	303	338

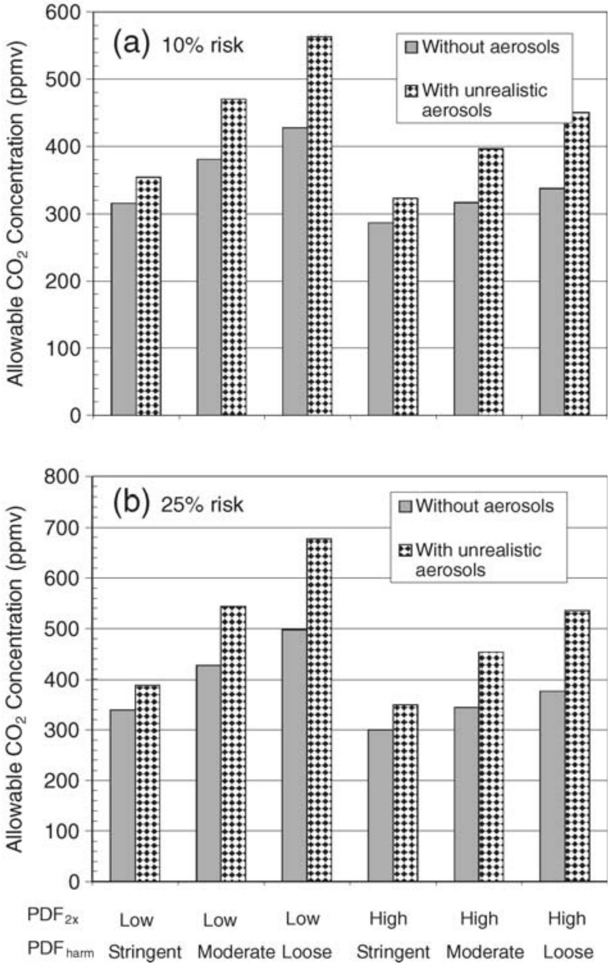
of the landscape (in the case of soil dust aerosols) produce a negative radiative forcing, thereby offsetting some portion of the radiative heating due to the buildup of greenhouse gases. Conversely, sooty (black carbon) aerosols have a positive radiative forcing, thereby adding to the heating effect of GHGs. There is a large uncertainty in all of the aerosol radiative forcings. Harvey and Kaufmann (2002), based on a comparison of observations with model simulations of global mean and hemispheric mean temperatures, deduced that the net effect of all aerosols was an offset of no more than half of the GHG radiative forcing by the 1990s. Knutti et al. (2002) obtained a similar result using a somewhat different observational constraint. It might be argued that the permitted radiative forcings derived in "Section 2.4" should be interpreted as the net radiative forcing based on GHGs and aerosols, rather than based on GHGs alone. This would permit a larger radiative forcing due to GHGs, and hence higher GHG concentrations, without violating the UNFCCC.

The magnitudes of the unknown aerosol radiative forcing and of the climate sensitivity are not independent of one another. This is because, if the climate sensitivity is large (5 K), the aerosol radiative forcing must be large (offsetting up to half the GHG forcing), while if the climate sensitivity is small (1 K) the net aerosol forcing must be close to zero, so that in either case the simulated temperature warming over the past century roughly matches the observed warming (see Harvey and Kaufmann 2002). Inasmuch as the climate response for a given GHG radiative forcing depends on the product of the climate sensitivity and the net radiative forcing, we can account for an aerosol offset of GHG forcing that is larger the assumed climate sensitivity by replacing $R_f\Delta T'$ with $R_{net}\Delta T'$ in the upper limit of the integral of PDF_{harm}, where R_{net} is the net radiative forcing. R_{net} is computed by assuming that aerosols offset a fraction of the GHG forcing that increases linearly from 0.0 at a climate sensitivity (ΔT) of 0 K to 0.5 at a climate sensitivity of 5 K, and is constant at 0.5 for any climate sensitivity greater than 5 K. Note that this relationship is really an assumption about the unknown *present day* aerosol forcing and how it must vary with the assumed climate sensitivity, so by applying it in Equation (1) as we integrate over all climate sensitivities for each GHG forcing that is considered, we are implicitly assuming that the same ratio of aerosol to GHG forcing will apply in the future as exists today. This is clearly not true; because of concerns over acid rain, aerosol forcing will decrease in the future relative to GHG emissions and hence relative to the total GHG forcing. This is exemplified by the SRES scenarios, described by Nakićenović et al. (2000), and in a recent update of the SRES sulphur emission scenarios by Smith et al. (2005). Thus, the procedure described above overstates the likely offset of GHG forcing by aerosols, and thus overestimates the GHG forcing that is allowed for any given risk tolerance and any combination of pdfs for climate sensitivity and harm.

Figure 3b shows the probabilities of harm as a function of the GHG radiative forcing ratio for the same six combinations of PDF_{2x} and PDF_{harm} as shown in Fig. 3a, when the associated climatic change used in PDF_{harm} at various sensitivities is reduced in the manner described above. As expected, the allowable GHG forcing ratios at a given risk tolerance all increase. For 10% risk tolerance, the allowable ratios change from 0.29–0.67 without aerosols to 0.47–1.10 with unrealistic aerosols. Figure 4 compares the allowed CO_2 concentration for 10% and 25% risk tolerance with and without aerosol forcing for the case where the radiative forcing by non-CO_2 GHGs is reduced in half.

Even though the above approach accounts for uncertainty in present-day aerosol radiative forcing, there are at least two reasons why the potential partial offset of GHG forcing by aerosols should not be included when deducing the allowable GHG forcing. First, as noted above, aerosol emissions are likely to be significantly reduced during the coming decades due to increasing concerns over acid rain pollution and the increasing

Fig. 4 Maximum allowed CO_2 concentrations with and without a partial aerosol offset of the GHG radiative forcing, assuming the non-CO_2 GHG forcing to be reduced to half the present forcing. Results are given for **a** a 10% risk tolerance, and **b** a 25% risk tolerance



willingness of an increasingly prosperous global society to address these concerns. Second, in combining aerosol radiative forcing with GHG radiative forcing, it is implicitly assumed that the spatial pattern of climatic change associated with aerosol forcing is the same as (but opposite in sign to) that associated with GHG forcing. While this is true for temperature in the majority of coupled atmosphere–ocean models (see Harvey 2004b), this is not true for precipitation. Furthermore, and as discussed in Harvey (2004b) and Feichter et al. (2004), aerosols have a disproportionately large effect in suppressing the increase in global mean precipitation that occurs with GHG warming, compared to their effect in suppressing the temperature increase. The reasons for this are well understood (Liepert et al. 2004). Inasmuch as a warmer climate tends to increase evaporation of soil water and the consequent drying of soils, the ratio of precipitation increase (over land) to temperature increase is critical to the impacts associated with climatic change. A net forcing resulting from a combination of GHG and aerosol heating tends to have a smaller ratio of precipitation to temperature increase than the same forcing caused solely by CO_2, so although aerosols reduce the warming associated with a given CO_2 increase, they do not necessarily reduce the impacts (or, at least, not as much as would be expected), given that

Table 3 Concentration of carbonate ions in the pre-industrial and present ocean surface layer, and under a doubling of atmospheric CO_2 (560 ppmv), as computed by ocean chemistry models and presented by Orr et al. (2005)

	$[CO_3^{2-}]$ (μmol/kg)			Percent saturation with respect to aragonite (%)			Percent saturation with respect to calcite (%)		
	PreInd	Present	$2\times CO_2$	PreInd	Present	$2\times CO_2$	PreInd	Present	$2\times CO_2$
Tropical	275	235	180	437	373	286	693	592	454
Global	220	183	148	349	290	235	554	461	373
Southern Ocean	112	90	63	178	143	100	282	227	159

Also given are the concentrations as a percent of the saturation value with respect to aragonite (63 μmol/kg) and calcite (42 μmol/kg)

less precipitation relative to warming will increase the risk and frequency of droughts. Thus, it is appropriate to neglect aerosol forcing when deducing the GHG forcing that is consistent with Article 2 of the UNFCCC.

2.6 Interference in the climate system and the broader Earth system through changes in ocean chemistry

Surface waters of the oceans are presently supersaturated with respect to calcium carbonate ($CaCO_3$). Calcium carbonate occurs in two mineral forms – aragonite, used as the structural material of corals and pteropods (high-latitude plankton), and calcite, used as the structural material of the foraminiferal and coccolith plankton groups. The absorption of CO_2 by the oceans reduces the degree of supersaturation by reducing the carbonate (CO_3^{2-}) concentration (which is consumed through the reaction $CO_2+H_2O+CO_3^{2-}2 \rightarrow 2\ HCO_3^-$). Simulations reported by Orr et al. (2005) for a doubling of atmospheric CO_2 concentration indicate a decrease in the degree of supersaturation with respect to calcite from about 700% to 450% in tropical regions, and from 280% to 160% in southern hemisphere polar regions (see Table 3 for results concerning both calcite and aragonite). The large decreases in the supersaturation with respect to calcite obtained with high emissions are likely to have profoundly negative impacts on marine ecology and productivity (Orr et al. 2005), and imply that a 'safe' atmospheric CO_2 concentration is well below a doubling of the pre-industrial concentration.

The higher concentration of aqueous CO_2 associated with decreasing carbonate concentration is likely to adversely affect marine macro-fauna (Pörtner et al. 2005). A mere 200 ppmv increase in CO_2 has been observed, in controlled experiments, to reduce the rate of growth of gastropods and sea urchins by up to 40% (Shirayama and Thornton 2005). Essentially nothing is known about the longterm effects on fish of sublethal concentrations of CO_2, but fish are likely to be sensitive to higher aqueous CO_2 concentrations because the difference between the CO_2 partial pressure in their body fluids and that of the ambient medium is an order of magnitude smaller than that of terrestrial animals (Ishimatsu et al. 2005).

3 Discussion

In the following sections, the implications of the above analysis for emissions policy and for research into climate sensitivity are briefly discussed.

3.1 Implications for emissions policy

A key finding of the analysis presented here is that, for a 10% risk tolerance, an atmospheric CO_2 concentration of 400 ppmv or less (i.e., close to the present concentration) violates the UNFCCC for every combination of pdfs for climate sensitivity and harm considered here if the radiative forcing by non-CO_2 GHGs is frozen at the present level, and for five out of six combinations of pdfs if the radiative forcing by non-CO_2 GHGs is reduced to half the present level. At 25% risk tolerance, four out of six cases still require a CO_2 cap of 400 ppmv or less, even if the forcing by non-CO_2 GHGs can be cut in half. From this it follows that GHG emissions need to be reduced as quickly as possible, not in order to comply with the UNFCCC, but in order to minimize the extent and duration of non-compliance. In particular, global fossil fuel use will need to be phased out before the end of this century, and that in turn requires a significant acceleration in the rate of reduction in energy intensity of the global economy (from 1%/year at present to 2.5%–3.0%/year until at least 2050, so as to achieve a factor of four reduction in energy intensity) and a rapid increase in the deployment of renewable sources of energy.[4] Depending on the ability to reduce energy intensity beyond a factor of four and to deploy renewable sources of energy, these measures may need to be accompanied by efforts to limit population growth (which have their largest effect after 2050) and a decrease in growth of GDP/person (particularly after 2050).

A second implication is that we do not have the luxury of trading off reductions in emissions of non-CO_2 GHGs against smaller reductions in CO_2 emissions. Rather, the most stringent possible reductions in emissions of CO_2, non-CO_2 GHGs, and of ozone precursors are simultaneously required.

A third implication is that, given that we have already overshot the 'safe' (i.e., allowable) CO_2 concentration for most of the PDF_{2x} and PDF_{harm} combinations considered here, preparations should begin for the creation of negative CO_2 emissions. Negative emissions can be created through the capture of CO_2 that is released from the combustion of sustainably grown biomass energy, and its injection into the deep ocean or into geological reservoirs. This process, known as 'carbon sequestration,' can begin with the capture of CO_2 from centralized sources (such as electric power plants) while fossil fuels are still being used, thereby speeding the reduction in fossil fuel emission, to be followed later by capture of CO_2 from biomass energy. It allows the atmospheric CO_2 concentration to be drawn down from its peak back to the 300–350 ppmv range over a period of 100–200 years, as illustrated in Harvey (2003, 2004a). However, carbon sequestration in the deep ocean cannot be relied upon in place of rapid reductions in the use of fossil fuels if one wishes to avoid eventual CO_2 concentrations that violate the UNFCCC, due to the fact that 10%–20% of the injected CO_2 will eventually outgas into the atmosphere (Harvey 2004a). As well, injection of significant amounts of CO_2 into the ocean could adversely impact deep marine life.

3.2 Implications for research concerning climate sensitivity

The shift from a focus on dangerous climatic change (as in the papers cited in the "Introduction") back to dangerous anthropogenic interference in the climate system (as in

[4] A comprehensive analysis of how to achieve a factor of 3–4 reduction in energy intensity in one particular sector, buildings (which account for about one third of global energy-related CO_2 emissions), is found in Harvey (2006a).

Article 2 of the UNFCCC) has implications concerning what we need to know with regard to climate sensitivity. If DAI is defined at the level of temperature changes, then one needs to know what the correct climatic sensitivity is in order to determine the allowable GHG emissions (and so, it could be argued, more research is needed to reduce the uncertainty in climate sensitivity before policy decisions can be made). However, if DAI is defined at the level of GHG concentrations, then one need only determine a plausible *upper limit* to the climate sensitivity in order to determine the concentrations that constitute DAI, and hence to determine what the global emissions targets should be.

This is not to say that it is not important to eventually determine what the true climate sensitivity is, or at least to reduce the uncertainty in its value. However, it may be another two–three decades before uncertainty in climate sensitivity can be reduced. In a follow-up paper (Harvey 2006b) it is shown that if one proceeds with aggressive reductions in fossil fuel CO_2 emissions (such that global emissions return to the 2010 level by 2020 and are heading downward), and it is definitively determined in 2020 that the climate sensitivity is no larger than 2 K, the CO_2 emission reductions achieved up to 2020 are still fully necessary in order to comply with the UNFCCC using a 10% risk threshold. Indeed, even with a climate sensitivity of only 2 K, emission reductions must continue for another two–three decades beyond 2020. Thus, reducing the uncertainty in climate sensitivity may reduce the need for emission reductions in the second half of this century, but has no implications concerning the need for emission reduction during at least the next three–four decades.

4 Summary and concluding comments

This paper has drawn attention to the importance of distinguishing between dangerous anthropogenic interference in the climate system and dangerous climatic change. A further distinction is drawn between dangerous climatic change and harmful climatic change. Two alternative pdfs for climate sensitivity have been considered here: one where 5% and 95% cumulative probabilities span the canonical range of 1.5–4.5 K (preferred here), and an alternative pdf with a 5%–95% cumulative probability range of 1.8–9.2 K, which is consistent with some recent work. It is also argued here that the pdf for the threshold in global mean temperature where significant harm occurs (PDF_{harm}) should have 10% and 90% cumulative values at warmings of 1 and 2 K, respectively. However, to test the robustness of the conclusions drawn using the preferred harm pdf, alternative harm pdfs with higher thresholds are considered. A third input that needs to be considered is the risk tolerance – that is, the largest acceptable probability that a given radiative forcing, given the climate sensitivity and harm pdfs, will result in significant harm to one or more of ecosystems, food production, and socio-economic systems. The choice of risk tolerance is a moral judgment, and should be low because it involves significant involuntary risks on others. However, risk tolerances of 10% and 25% are considered here purely for illustrative purposes.

For a 10% risk tolerance, the current CO_2 concentration is found to already violate the stated goal of the UNFCCC of preventing dangerous anthropogenic interference in the climate system for every combination of PDF_{2x} and PDF_{harm} considered here, if non-CO_2 GHG forcing is merely frozen at its current value. If non-CO_2 GHG forcing can be reduced in half, the current CO_2 concentration still violates the UNFCCC for every combination of pdfs considered here except one. At a 25% risk threshold (considered here only for illustrative purposes), the current CO_2 concentration still violates the UNFCCC in four out of six cases if non-CO_2 radiative forcing is cut in half, and in five out of six cases if it is frozen at the current level. Negative aerosol forcing cannot be relied upon to offset some of the GHG heating because aerosol emissions will fall in the future even if CO_2 emissions continue to grow, and because aerosols disproportionately suppress the increase of precipitation (to the extent that it increases at all) relative to the increase of temperature, thereby worsening the likely impact for a given temperature increase.

The most important conclusion of this work is that, assuming a 10% risk tolerance and present non-CO_2 radiative forcing, the current concentration of CO_2 (380 ppmv) violates the UNFCCC for every combination of climate sensitivity and harm-threshold pdf considered here, including pdfs that are highly optimistic concerning climate sensitivity or the resilience of natural ecosystems and the Greenland and West Antarctic ice sheets. However, it could be argued that a 10% risk tolerance is too high, as it translates into a 1-in-1,000 to a 1-in-10,000 risk of death to individuals, which is a 100- to 1,000-fold greater risk than the 1-in-one million risk used by the US Environmental Protection Agency and Nuclear Regulatory Commission. If a lower risk tolerance is adopted, then the current CO_2 concentration is unquestionably in violation of the UNFCCC. This conclusion is in stark contrast to that of Wigley (2004), who concluded that there is only a 17% chance that the CO_2 concentration needed to avoid DAI should be less than the present concentration, and a 50% chance that the allowable CO_2 concentration could be as large as 536 ppmv.

Independently of the climate sensitivity, CO_2 concentrations well below a doubling (560 ppmv) will cause biologically significant changes in ocean chemistry, likely with serious negative consequences for marine productivity, the marine biological pump, and the carbon cycle (provoking a positive climate–carbon cycle feedback). This is another way in which elevated CO_2 concentration constitutes dangerous anthropogenic interference in the climate system, or at least in the broader Earth system.

As shown here, the risk-averse nature of Article 2 of the UNFCCC requires immediate and stringent reductions in emissions of all GHGs. That is, immediate and stringent reductions are required *because of* scientific uncertainty, not in spite of uncertainty. Uncertainty, however, has been used as a reason for delay of emission reductions, presumably on the grounds that future knowledge may show that near-term emission reductions are unnecessary. In a follow-up paper (Harvey 2006b) it is shown that, even if the climate sensitivity were definitively determined in 2020 to be no more than 2 K, stringent emission reductions between now and 2020 are still required.

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