CHOOSING A STABILIZATION TARGET FOR CO_2

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Article 2 of the UN Framework Convention on Climate Change (UNFCCC) provides a key and much-quoted statement that is meant to guide us in our efforts to stabilize the effects of mankind on the climate system. 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 ….. 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".

This is a strong yet frustratingly vague statement, and scientists and policy makers have been agonizing over the meaning of 'dangerous interference' ever since the UNFCCC was published. It raises other important questions. Even if the 'dangerous interference' concept were well defined, what would this mean for choosing a stabilization target for CO_2 and the other greenhouse gases that we produce? … and, given such targets, what pathway should we take towards stabilization, given that the pathway may determine whether or not we can keep the rates of climate change within tolerable (i.e., non-dangerous) limits? In this editorial, I will attempt to put these issues into a probabilistic framework that may help to clarify thinking on this complex subject and act as a first step towards the quantification of the many uncertainties that surround it. A complementary analysis has been given by Mastrandrea and Schneider (2004).

The wording of Article 2 implies that there is a specific threshold of some variable or metric above which changes in climate might be considered 'dangerous'. This is clearly an oversimplification. Notwithstanding the ambiguity of the word 'dangerous', what is deemed dangerous in one economic sector or geographical region may be far less consequential in another. Furthermore, what is dangerous now may not be dangerous in the future, given that economic development generally reduces a society's vulnerability to climate change; and what is a dangerous change in one climate variable (such as precipitation) may occur in conjunction with an innocuous or even beneficial change in another (such as temperature). There is no way that we can fully account for these complexities.

We can, however, hope that the multifaceted aspects of the problem can be captured through a single metric, such as global-mean temperature. The appropriate temperature to consider, since we are dealing with a basically stable climate situation, is the equilibrium (i.e., eventual) temperature corresponding to a particular forcing level, in turn corresponding to a particular CO_2 concentration stabilization level. Even with a single metric, however, it is impossible to choose a specific threshold. I will therefore eschew the idea of a specific threshold and replace it with a probabilistic representation.

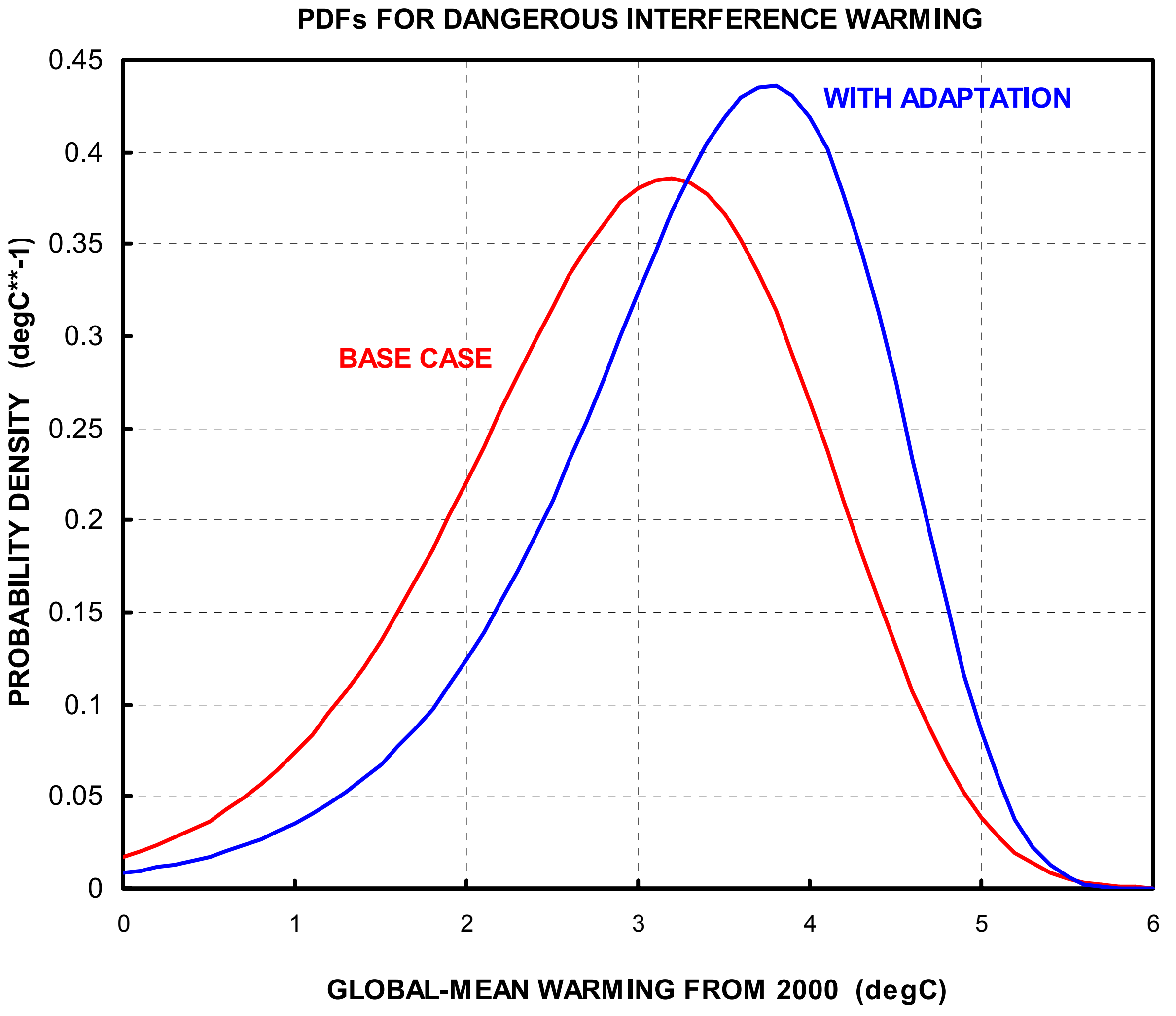
I will assume that for any given change in equilibrium global-mean temperature there is a probability that this change should not be exceeded. This corresponds to expressing the dangerous interference threshold as a probability density function (pdf), whose spread captures the many uncertainties surrounding the dangerous interference concept. Of course, defining such a pdf is, itself, fraught with uncertainty – but, as our understanding advances, we can easily change the pdf. One can also change the pdf to investigate sensitivities to its position and shape.

In addition, the pdf method allows one to investigate issues like adaptation (either spontaneous or policy-driven). Since adaptation reduces vulnerability, a better adapted society or economic sector will be able to endure greater magnitudes of climate change before reaching levels of dangerous interference. Thus, the effects of adaptation may be captured by shifting the pdf for global-mean temperature to higher temperatures. I will explore this issue further below.

The temperature-threshold pdfs used here are shown in Fig. 1. Temperatures are measured relative to today (nominally the year 2000). The base-case pdf is based on the IPCC's 'Reasons for Concern' (or 'burning embers') diagram (Smith et al., 2001, Fig. 19-7; color versions of the diagram appear in the Working Group II Summary for Policymakers, on p. 5 and p. 71), and more recent literature such as O'Neill and Oppenheimer (2002) and Hitz and Smith (2004). From the IPCC Figure, even with no future warming the judgment is that there is some risk of dangerous interference to what are currently 'unique and threatened systems', while above approximately 5°C future warming in all sectors becomes subject to 'higher risk'. In the central concern category, impacts transition from 'negative for some regions' to 'negative for most regions' at a global-mean warming between 3°C and 4°C.

From this, I have assumed conservatively that the median of the temperature threshold distribution is 3.0°C. I have also assumed that there is some higher warming level above which we can be virtually certain that there will be widespread dangerous interference, and that there is a finite but small probability that we have already passed the dangerous interference level. These two criteria are captured by using a log-normal distribution, with a 90% confidence interval of 1.0–4.5°C. The theoretical upper bound of this distribution is 9.0°C (although above 5.7°C the probability that the threshold is not exceeded is vanishingly small, so 5.7°C is the effective upper bound); and the probability that we have already exceeded the dangerous interference level is small but finite, approximately 1%. These are somewhat arbitrary choices. While they are consistent with the wide spread of views expressed in the literature, they must be treated with some circumspection. The main point here is to provide a quantitative probabilistic framework for investigating the consequences of dangerous interference vis a vis a stabilization target for CO_2 concentration.

Fig. 1: Assumed pdfs for the dangerous-interference warming threshold for global-mean temperature change from 2000.



Knowing the dangerous interference threshold (probabilistically) is the first step towards defining a CO_2 concentration target. To fully define the target we need to know the contributions of non-CO_2 gases to future climate change in terms of radiative forcing (which, together with the CO_2 forcing gives the total forcing on the climate system), and the relationship between radiative forcing and the eventual warming (which is determined by the climate sensitivity). We need, therefore, to define these two other factors (non-CO_2 forcing and climate sensitivity) in probabilistic terms. Again, the uncertainties inherent in doing this should be noted.

For the climate sensitivity, I employ the log-normal pdf used in Wigley and Raper (2001) – see Fig. 2. The justification for this pdf is given in the original reference. There are, of course, other sensitivity pdfs in the literature (e.g., Andronova and Schlesinger, 2001; Forest et al., 2001, Gregory et al., 2002).

For non-CO_2 forcing, I use information from the SRES scenarios (Nakicenovic and Swart, 2000), and I assume that no policies are introduced to reduce this component of overall forcing. Of course, Article 2 is not restricted to CO_2 alone, so, if we abide by Article 2, then efforts will doubtless be made to stabilize the concentrations of other greenhouse gases. Indeed, it may well be more cost-effective and less technologically challenging to stabilize some of these gases more rapidly than CO_2 (see, e.g., Manne and Richels, 2001). Furthermore, efforts to stabilize CO_2 will also affect the concentrations of other gases because they have sources in common, so it is not strictly correct to decouple CO_2 and non-CO_2 gases. The reason for doing so here is because the no-policy case for non-CO_2 gases provides an important baseline. It is straightforward to generalize this case by assuming some level of coupling; and one can easily investigate sensitivities to non-CO_2 mitigation policies by shifting the pdf for non-CO_2 forcing to lower values – see below.

For the SRES scenarios, if aerosol forcing uncertainties are accounted for as in Wigley and Raper (2001), the range of non-CO_2 forcing (CH_4, N_2O, tropospheric and stratospheric ozone, various halocarbons and SF_6, and sulfate, carbonaceous and other aerosols) from pre-industrial times to 2100 lies in the range 0.2–2.7W/m^2. I assume, therefore, that non-CO_2 forcing can be described by a Gaussian pdf with a mean of 1.5W/m^2 and a 90% confidence interval of 0.5–2.5W/m^2; see Fig. 3.

Fig. 2: Assumed pdf for climate sensitivity (from Wigley and Raper, 2001).

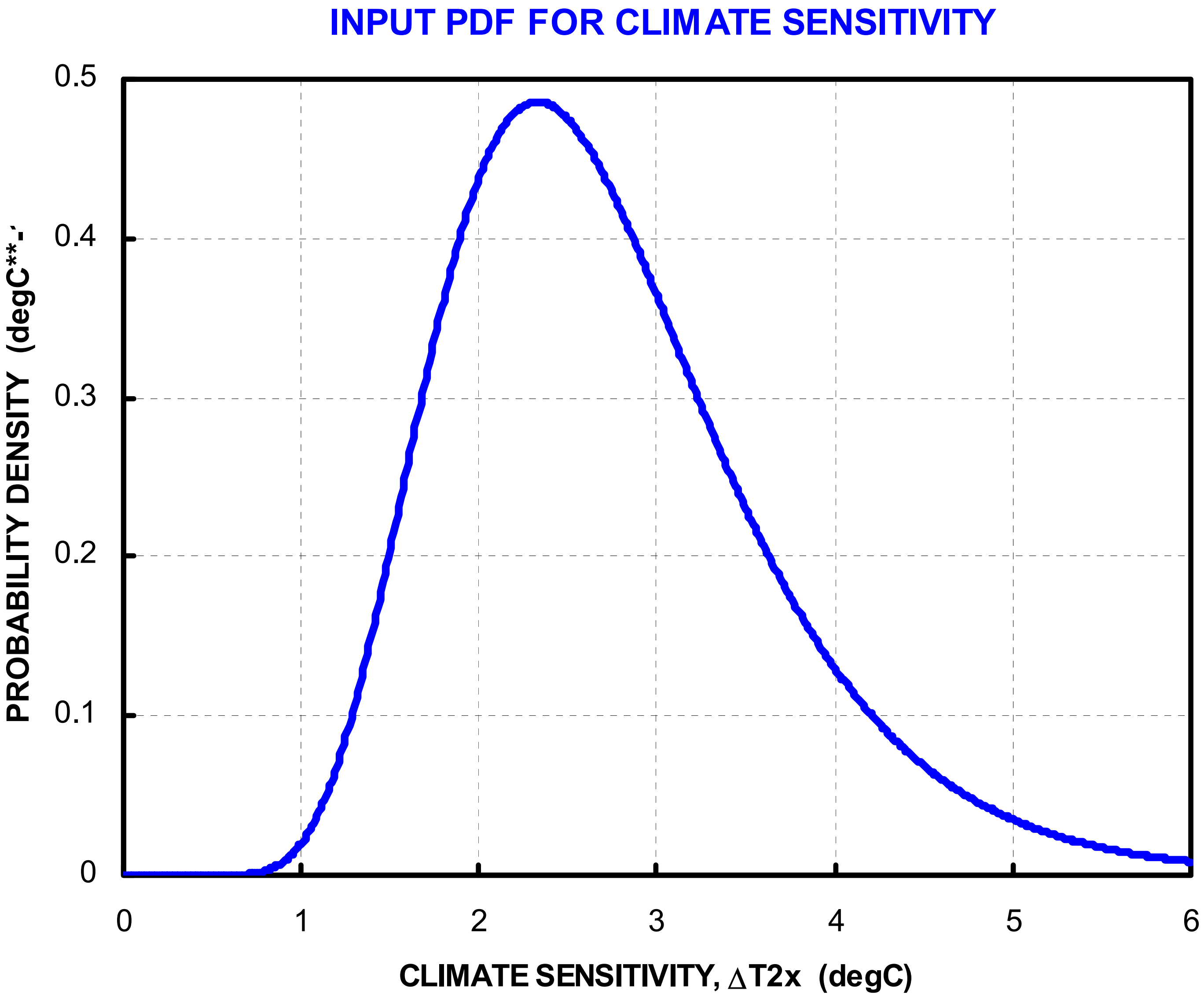
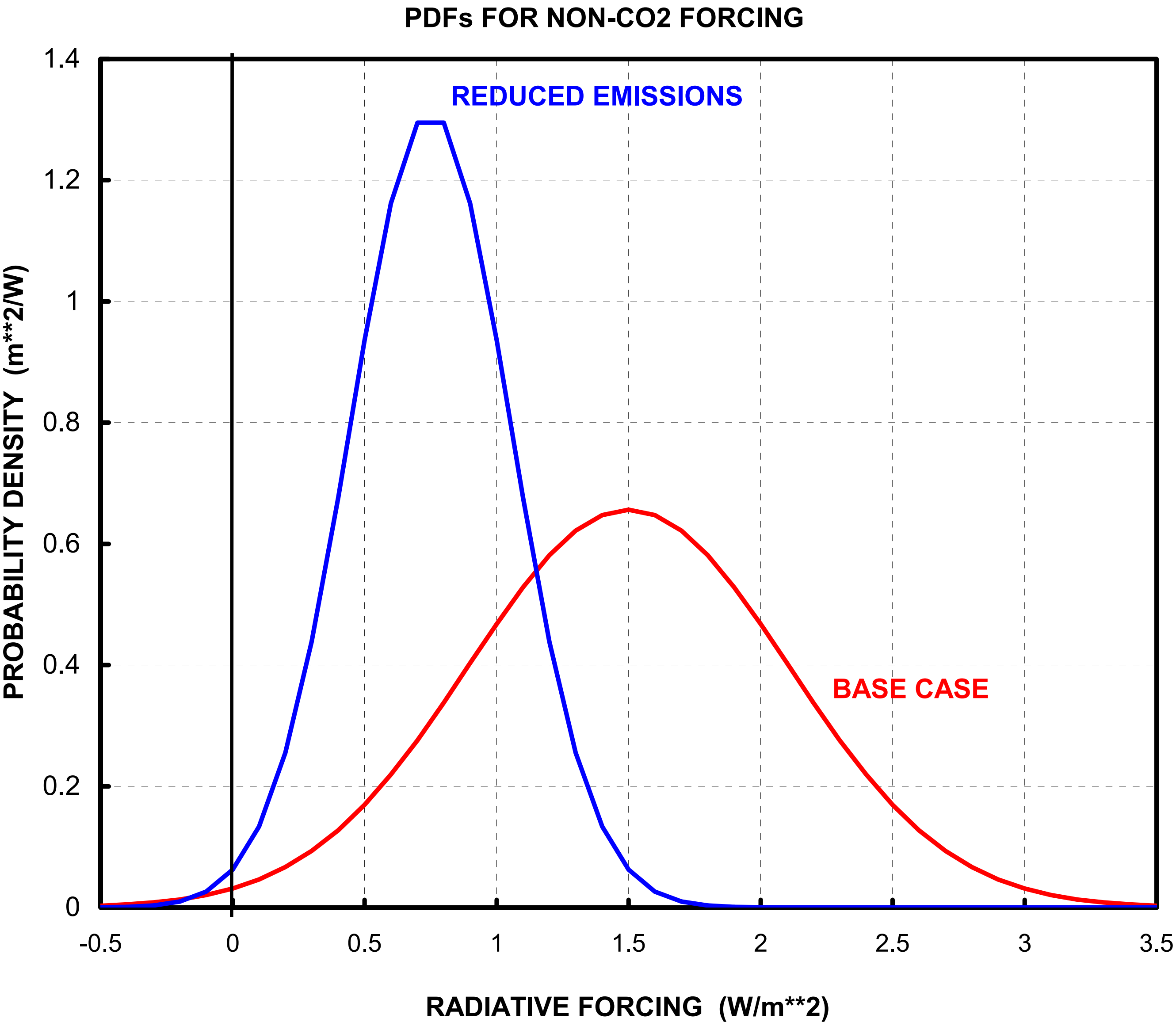


Fig. 3: Assumed pdfs for total radiative forcing from all non-CO_2 sources (including aerosols). The base case is based on the SRES scenarios, while the reduced emissions case halves the base case statistics. The base-case pdf corresponds to forcing from pre-industrial times to 2100, and the 2100 level is assumed to be the upper bound for such forcing.



Figures 1–3 provide all the information that is required to determine the pdf for the CO_2 stabilization level, C_{stab}, that corresponds to any given dangerous-interference warming threshold. The relationship between C_{stab} and equilibrium warming, climate sensitivity and non-CO_2 forcing may be derived as follows. First, the equilibrium warming (ΔT) for any forcing level ΔQ is determined by

$$\Delta T = \Delta Q(\Delta T2x/\Delta Q2x)$$

where 'Δ' denotes change from pre-industrial times, $\Delta T2x$ is the climate sensitivity and $\Delta Q2x$ is the radiative forcing for $2xCO_2$ (= 5.35 ln(2) = 3.71 W/m^2; this is the best estimate given in the IPCC Third Assessment Report). If DT is used to denote the global-mean temperature change from 2000, then

$$\Delta T \cong DT + 0.7$$

where 0.7^oC is the warming from pre-industrial times to today (assumed to be slightly more than the warming over the 20th century). Also, total forcing may be divided into CO_2 and non-CO_2 ('other') parts to give

$$\Delta Q = \Delta QCO_2 + \Delta Qother$$

where

$$\Delta QCO2 = 5.35 \ln(C_{stab}/278).$$

with 278ppm being the pre-industrial CO_2 concentration. From these relationships we obtain

$$(DT + 0.7)/\Delta T2x = \ln(C_{stab}/278)/\ln(2) + DQother/(5.35 \ln(2))$$

from which we find

$$C_{stab} = 278\ [2^{\{(DT+0.7)/\Delta T2x - \Delta Qother/3.71\}}]$$

where DT is the dangerous-interference warming threshold measured from the year 2000. Given pdfs for DT, $\Delta T2x$ and $\Delta Qother$, it is a simple matter to derive the pdf for C_{stab}. The three input pdfs are first divided into fractiles and median values are taken for each fractile. If there are, say, 10 fractiles for each pdf, then there will be 1000 equally probable combinations of these fractile medians that may be substituted into the C_{stab} expression. These 1000 C_{stab} results may then be combined into an output pdf, as shown in Fig. 4.

Fig. 4: Probability density function for the CO_2 concentration target required to avoid dangerous interference with the climate system, based on the input pdfs shown in Figs. 1–3 (base cases). The left vertical line is the present concentration level, and 17% is the probability that the dangerous interference threshold has already been exceeded.

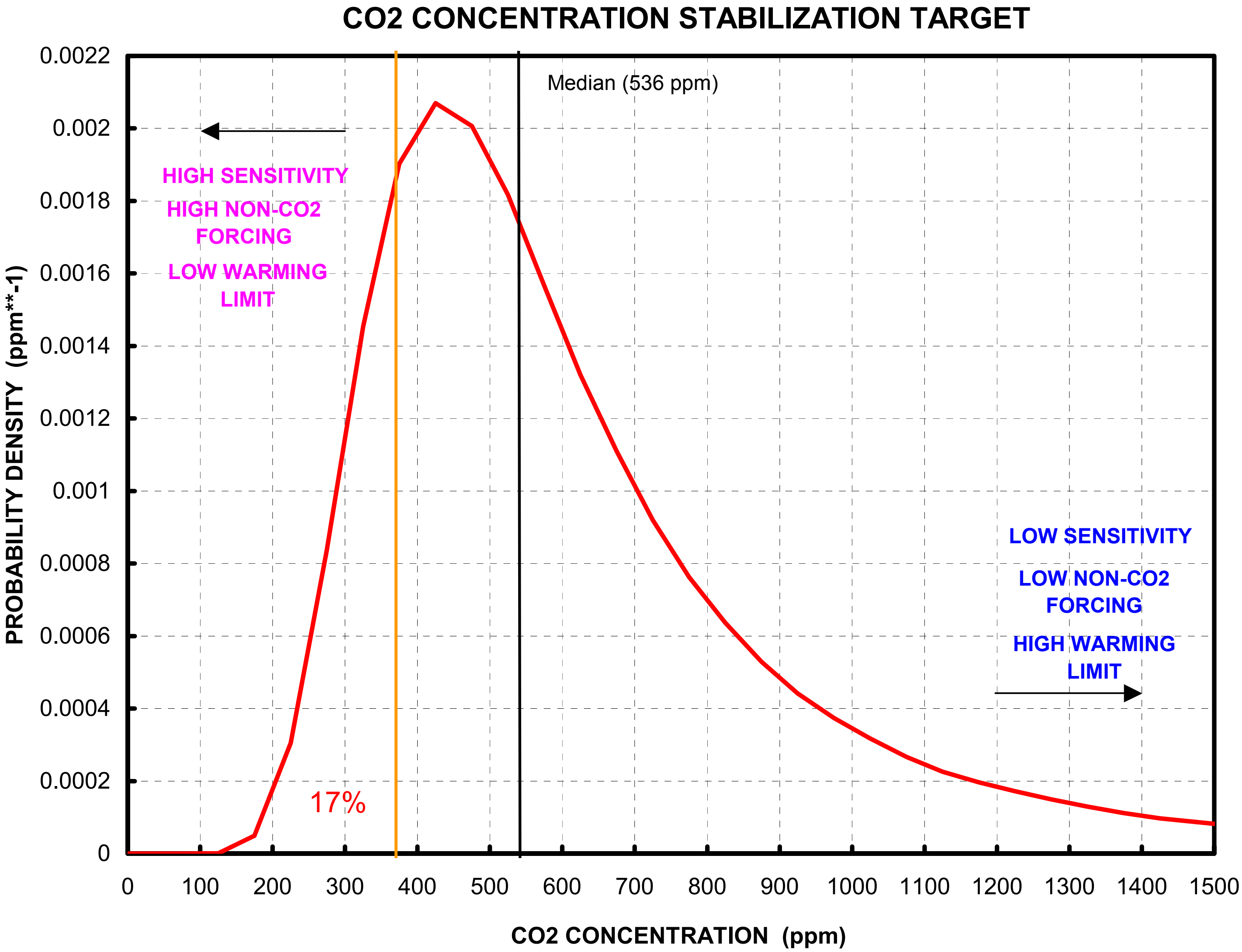


Figure 4 quantifies the large range of uncertainty in specifying a stabilization target for CO_2. The median value is 536ppm. There is, however, a 17% probability that the stabilization target required to avoid dangerous interference might be less than the present concentration level – corresponding to the case where future non-CO_2 forcing is large, the climate sensitivity is high and the dangerous-interference warming threshold is low. Policies directed towards reducing non-CO_2 forcing, and/or towards reducing society's vulnerability to climate change could reduce this probability substantially. (The issue of reducing non-CO_2 forcing is a complex one. It embraces all non-CO_2 gases, including reactive gases and aerosol precursors. For some of these gases, relative to their emissions in the SRES scenarios, emissions are likely to be reduced even in the absence of climate policies – see Wigley et al., 2002.) At the other extreme, if non-CO_2 forcing and the climate sensitivity were low, and the dangerous interference threshold were high, then the CO_2 stabilization target could be very high (the probability that it is more than 1000ppm, in the present 'base case' analysis, is 9%).

At this end of the range of stabilization levels, of course, other issues beyond climate would need to be considered. An atmospheric concentration of 1000ppm or more would lead to a considerable reduction in ocean pH, which could have adverse effects on carbonate shell-producing animals, and on the marine food chain that depends on these animals. Such high CO_2 levels might also change the buffer factor by shifting the ocean chemistry constraint from constant alkalinity to constant carbonate-mineral saturation index (see, e.g., Sundquist et al., 1979).

As noted above, the CO_2 stabilization target pdf could be changed either through adaptation or by reducing the forcing from non-CO_2 sources. To illustrate these possibilities, as a sensitivity analysis, I modify the pdfs for the temperature threshold and non-CO_2 forcing. The new pdfs are shown in Figs 2 and 3. For adaptation I assume that such strategies have a greater effect at low threshold levels (since higher threshold events – such as a catastrophic melting in Antarctica or Greenland, or a rapid shut down of the thermohaline circulation -- are more likely to involve climate or sea level changes that are beyond any feasible adaptive capacity). Instead of a median of 3.0°C and 90% confidence interval of 1.0°C to 4.5°C, I choose 3.5°C and 1.5°C to 4.75°C. The effective upper bound remains as before at 5.7°C, while the probability that we have already passed the dangerous interference temperature threshold drops to 0.6%. A summary of the changes in the temperature threshold pdf is given in Table 1. For non-CO_2 forcing I simply halve the median and 90% confidence interval values.

Results for these revised pdfs, separately and together, are shown in Fig. 5 and Fig. 6. The effects of adaptation and non-CO_2 emissions reductions on the concentration-target pdf are summarized in Table 2. Both policies lead to substantial shifts in the stabilization-target pdf towards higher concentrations. Together, they have still larger influences; for example, the median concentration target rises from 536ppm to 680ppm. The probability that the target should be less than today's concentration level (taken as 370ppm) reduces from 17% in the base case to less than 4% in the 'both' case; the probability that the target should be less than the canonical 550ppm (roughly double the pre-industrial level) reduces from 53% in the base case to about 29% in the 'both' case; and the probability that the target could be more than 1000ppm increases from about 9% in the base case to 18% in the 'both' case.

Fig. 5: Probability density functions for the CO_2 concentration target required to avoid dangerous interference with the climate system: effects of adaptation, reductions in forcing from non-CO_2 gases, and both factors. The base case is the same as in Fig. 4.

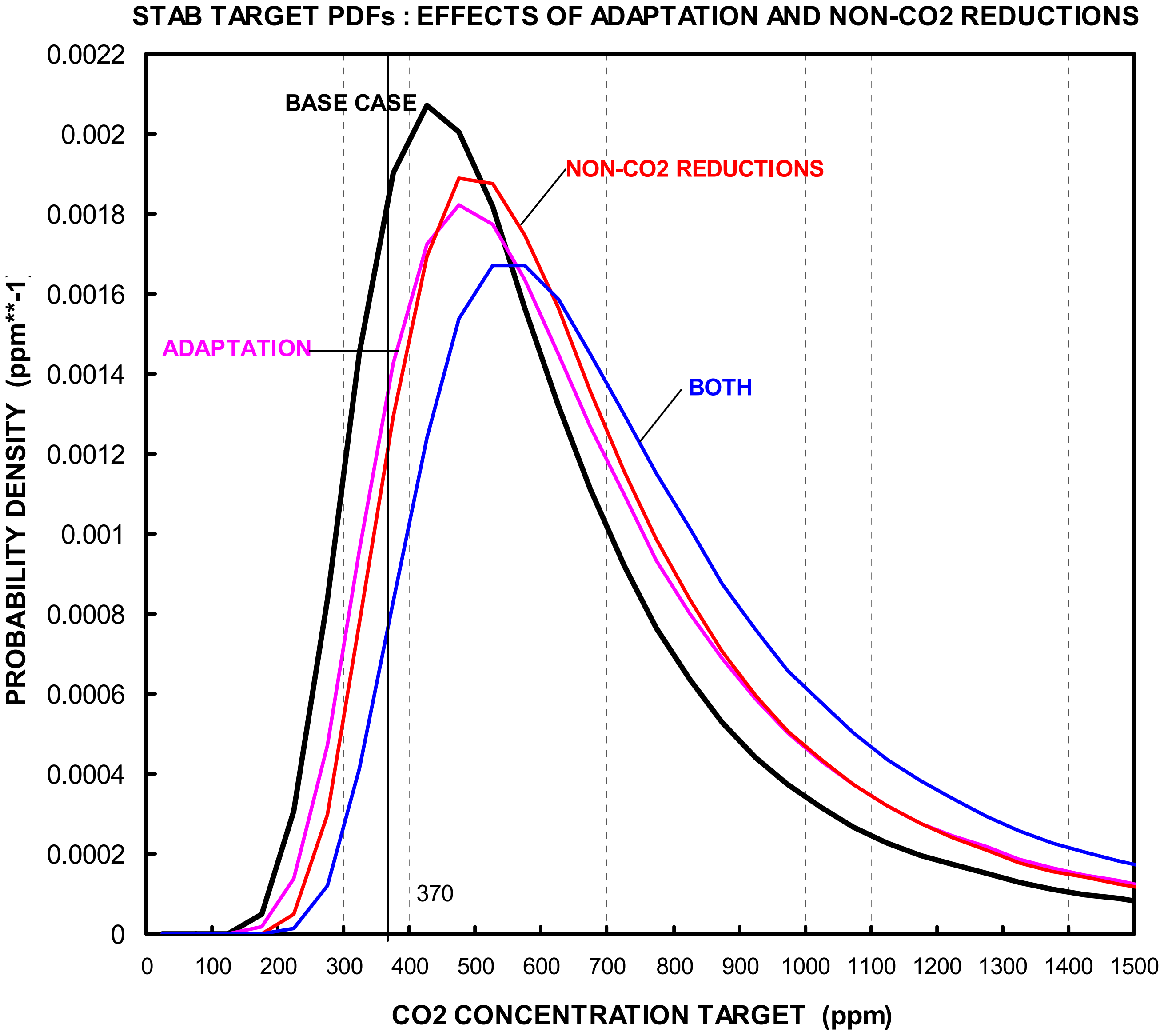
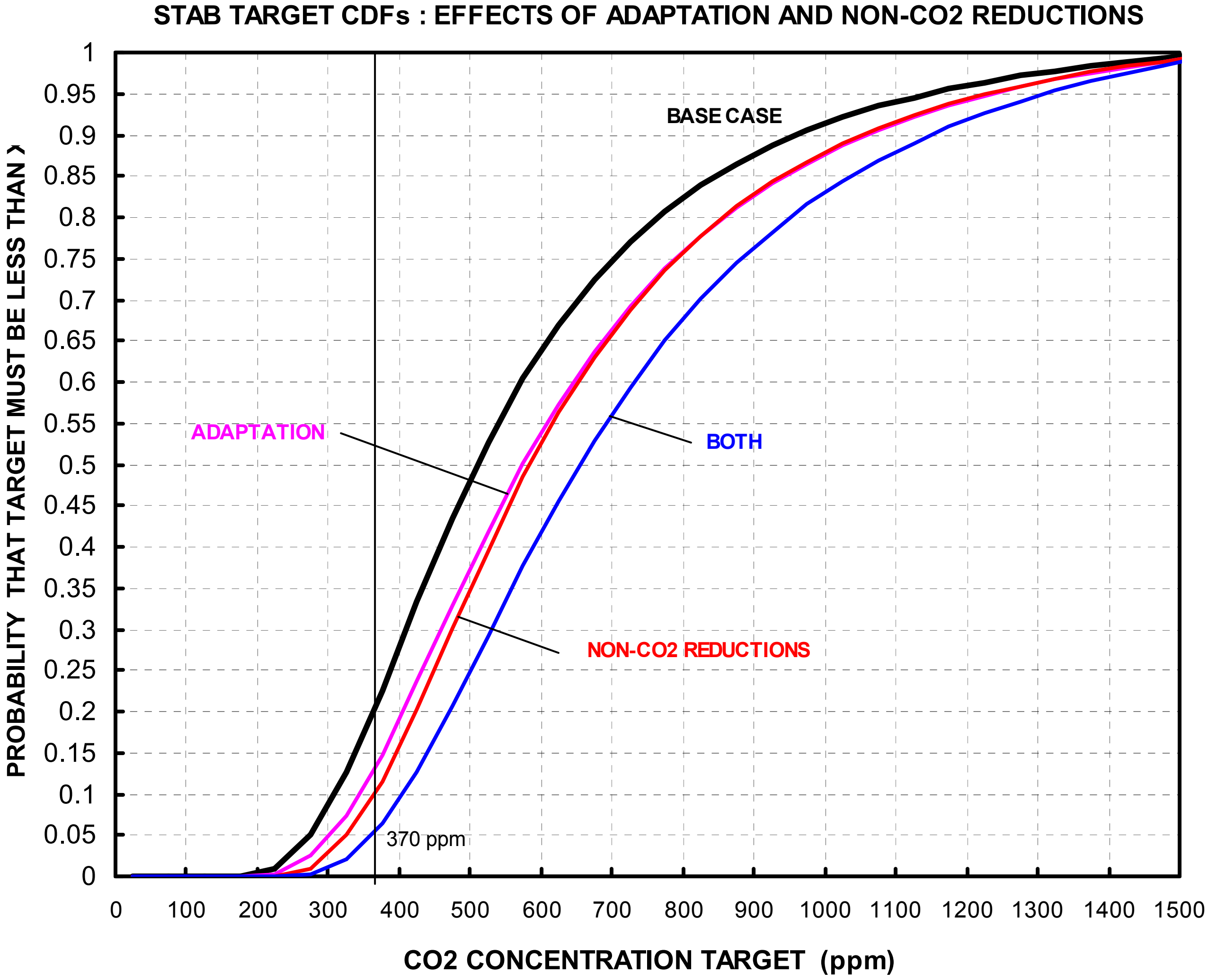


Fig. 6: Cumulative probabilities for the CO_2 concentration target required to avoid dangerous interference with the climate system: effects of adaptation, reductions in forcing from non-CO_2 gases, and both factors. The ordinate gives the probability that the target must be less than the corresponding x-axis value. This is the cumulative probability version of Fig. 5.



These numbers should be taken as indicative of overall probabilities and their sensitivities to modification through adaptation or non-CO_2 mitigation policies rather than definitive results, and they are clearly dependent on the various assumptions that I have made. For example, the changes that I have assumed for the dangerous interference and non-CO_2 forcing pdfs are somewhat ad hoc, but they are not unrealistic. For non-CO_2 forcing, the ‘policy’ pdf that I have assumed may, in fact, be a more realistic future possibility than the base case, since it is known that the SRES emissions scenarios are unrealistically high for some of the non-CO_2-gas precursors (Wigley et al., 2002). For the adaptation case, we currently have no quantitative understanding of the scope for shifting the dangerous interference distribution to higher warming levels through such strategies. The changes that I have assumed, moving the threshold warmings up by 0.5^{o}C for all but the upper bounds of the distribution, seem modest. There have been no attempts to express either of these policy instruments in probabilistic terms in the literature, but the value of so doing is clear.

The high CO_2 results warrant further consideration. Although it is possible that one might avoid dangerous interference with the climate system with CO_2 levels in excess of 1000ppm, such levels may lead to adverse effects on marine chemistry and biology and on the carbon cycle. Whether or not the carbon cycle can be construed as part of the climate system is an interesting question. The possibility arises of not reaching the dangerous interference threshold for ‘climate’ *senso stricto*, but still passing a CO_2 threshold that either did not “allow ecosystems to adapt naturally” (marine ecosystems that is) and/or failed “to ensure that food production is not threatened”. One of the ironies here is that reducing climate change through mitigation of non-CO_2 emissions or through adaptation increases the risk of damaging consequences to the carbon cycle.

Choosing a stabilization target for CO_2 is essentially a risk assessment problem, where the choice depends on what is deemed to be an acceptable risk. For example, if we were to choose the median target in the base case, 536ppm (and ignore the effects of non-CO_2 mitigation and adaptation), are we willing to accept a 50% probability that such a target may lead to unacceptable damages? Given the unequal distribution of damages across time, economic and environmental sectors, and geographical location, this is a very difficult question to answer. It is hoped that the probabilistic results presented here can serve as a first step towards better quantifying and communicating these risks.

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Table 1: Assumed probabilities (in %) that the warming threshold is less than specific values from $0^{o}C$ to $5^{o}C$ for the base-case pdf and the adaptation modification.

THRESHOLD	**0.0**	**1.0**	**2.0**	**3.0**	**4.0**	**5.0**
BASE CASE	1.0	5.0	18.9	50.0	85.1	98.7
+ ADAPTATION	0.6	2.5	9.7	31.2	71.5	98.2

Table 2: Key distribution characteristics for the CO_2 stabilization-target pdfs: base case, with adaptation, with emissions reductions for non-CO_2 gases, and with both non-CO_2 reductions and adaptation. p(C < 370; etc.) denotes 'probability of the stabilization level having to be less than 370ppm' (etc.), expressed in %. Median concentrations are in ppm.

SCENARIO	**p(C < 370)**	**P(C < 550)**	**p(C > 1000)**	**Median conc.**
BASE CASE	16.6	52.6	9.4	536
+ ADAPTATION	10.3	41.8	13.4	599
+ NON-CO2 REDUCTIONS	7.6	39.6	13.3	610
+ BOTH	3.9	29.1	18.4	680