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Alternatives to stabilization scenarios

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[1] Studies attempting to constrain climate sensitivity, or equilibrium surface warming in response to a doubling of atmospheric carbon dioxide, by comparing models with observations report a wide range of distributions, particularly regarding the upper bound. There is, by contrast, a considerable consensus surrounding the transient climate response, in large part because it is directly related to observed warming attributable to greenhouse gases. We argue that scenarios which can exploit this consensus may be preferable to stabilization scenarios for practical policy-making purposes. The difficulty of ruling out a high equilibrium warming response to elevated carbon dioxide levels may provide an opportunity for reassessment of the stabilization scenario as the centerpiece of climate policy in favour of scenarios that are more directly constrained by the transient response.
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1. Introduction

[2] Equilibrium climate sensitivity, *S*, is usually considered a key determinant of climate change [*Houghton et al.*, 2001] and climate change policy [*Houghton et al.*, 2001; *Mastrandrea and Schneider*, 2004]. Numerous recent studies [*Andronova et al.*, 2006; *Murphy et al.*, 2004; *Hansen et al.*, 2005] have attempted to determine a range of climate sensitivities consistent with recent observations of the climate. A common feature has emerged: while observational data can help rule out climate sensitivities lower than 1–2°C, there is no corresponding robust observational constraint on the upper bound. Much of this variation arises from the lack of any recent observations which scale with sensitivity, but it is also compounded by different prior assumptions regarding climate sensitivity. The reason for this lack of a robust upper bound on climate sensitivity appears to be quite fundamental, and hence unlikely to be overcome by any "magic bullet" observation in the near future. Studies that do report relatively low upper bounds [e.g., *Murphy et al.*, 2004] are constrained primarily by prior assumptions (how much weight is given to different sensitivities before any comparison with observations is made) rather than by actual climate data [*Frame et al.*, 2005]. The discovery [*Stainforth et al.*, 2005; *Piani et al.*, 2005] of general circulation models (GCMs) with sensitivities much higher than the traditional IPCC range that provide as comparable a fit to observations as traditional GCMs reinforces this point.

[3] There are three fundamental reasons for the lack of a robust upper bound on climate sensitivity. First, feedbacks in a much warmer world may be very different from any we have observed [*Senior and Mitchell*, 2000]. Second, and more importantly for studies using recent data, even if sensitivity is constant as we examine high values, observable quantities tend to scale with the strength of atmospheric feedbacks [*Allen et al.*, 2005], which are inversely proportional to *S*. This means if uncertainty in the observable quantity conforms to something like a Gaussian distribution, we derive an inverse Gaussian – with the attendant fat tail at high values – for the likelihood function for sensitivity. Hence if any aspect of uncertainty in an observable quantity is normally distributed, we must find a non-zero likelihood of an arbitrarily small net feedback and hence no upper bound on *S* unless it is imposed by prior assumption. Given the chronic inability to provide a compelling upper bound on *S* we suggest below that scenarios that exploit the consensus surrounding the transient response may provide better-constrained alternatives to stabilization scenarios. The third, closely related reason for the lack of a robust upper bound on climate sensitivity is the difficulty in choosing an appropriate "prior" or weighting strategy for the combination of models and data used in the study, independently of the models and data being used in the study itself [*Frame et al.*, 2005].

2. Method

[4] *Frame et al.* [2005] examined the relationship between *S* and global mean twentieth century warming attributable to greenhouse gases [*Stott and Kettleborough*, 2002] for a range of versions of a simple climate model that are consistent with both attributable greenhouse warming and effective heat capacity inferred from ocean heat content changes. In the analysis that follows we use the same perturbed-physics energy balance model ensemble forced with greenhouse gases throughout the 20th and 21st centuries, in conjunction with the results of *Stott et al.* [2006] which combine three separate GCM detection and attribution studies. The use of attributable warming as our temperature variable (and greenhouse forcing) allows us to avoid problems associated with uncertainty in sulphate forcing [*Gregory et al.*, 2002; *Knutti et al.*, 2002; *Andreae et al.*, 2005], because future warming is more linearly related to past greenhouse warming than it is to total twentieth century warming. Heat capacity is inferred from the observed change in global mean heat content [*Levitus et al.*, 2005] over the 1957–94 period divided by the corresponding change in decadal-mean surface temperature

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[*Jones et al.*, 1999], allowing for the uncertainty in both quantities. This gives us a range of effective ocean heat capacities similar to those used by *Andreae et al.* [2005]. This approach contains the implicit assumption that heat capacity is the same in the case of greenhouse-only forcing as it is in the all forcings case. If we examine this assumption by including all past forcings for comparison, we find the upper bound on *S* decreases by around 10%, but virtually no change in estimated warming rates, because the distribution of warming rates consistent with past observations is to a very good approximation independent of effective heat capacity. Given the known deficiencies in simple model responses to short-term forcing, we believe the approach taken here, focusing on the model response to greenhouse gases, is best justified, but the fact that the upper bound on *S* is sensitive to the precise method of estimating effective heat capacity further emphasises its lack of robustness. Following *Frame et al.* [2005] we choose our predictive distributions such that they are uniform in the forecast variable. This corresponds to a uniform prior in *S* when we are forecasting *S*, a uniform prior in the transient climate response (TCR) where we are looking to forecast TCR, and a uniform prior in the maximum warming under a containment scenario when that is the forecast variable.

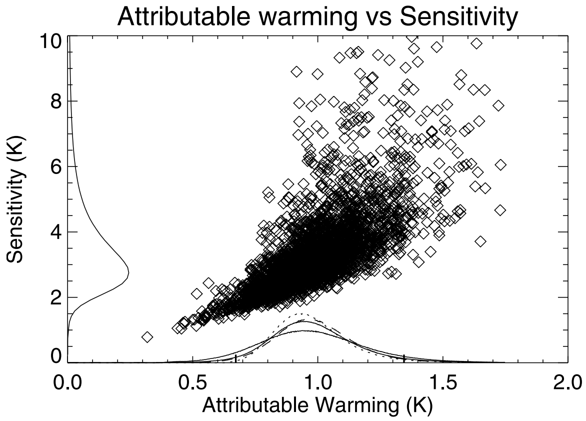

Figure 1. Relationship between the current rate of greenhouse gas-induced warming inferred from 20th century temperature changes and equilibrium climate sensitivity, for an observationally constrained perturbed physics energy balance model ensemble following *Frame et al.* [2005]. Also shown are likelihood distributions for attributable warming from 3 models (HadCM3, solid curve; PCM; dotted curve; GFDL, dashed curve) and climate sensitivity (distribution at left). The three model average (and associated 5–95% range) is shown as the heavier line on the bottom axis.

3. Results

[5] The diamonds in Figure 1 show *S* plotted against 20th century warming attributable to greenhouse gases [*Stott and Kettleborough*, 2002] for an observationally-constrained ensemble of simple climate models [*Frame et al.*, 2005]. The transfer function relating attributable warming to climate sensitivity tends toward vertical as *S* increases, providing no effective upper bound. This problem of a non-linear relationship between observable quantities and *S* was noted long ago in the context of simple models [*Hansen et al.*, 1985] and more recent studies have demonstrated it also applies in GCMs [*Murphy et al.*, 2004; *Piani et al.*, 2005; *Knutti et al.*, 2006]. The implication is that the risks associated with any stabilization or equilibrium-based scenario remain critically dependent on subjective prior assumptions because of our inability to find directly observable quantities that scale with sensitivity. Thus any attempt to use sensitivity as a scientific and policy variable suffers from an inability to find a robust upper bound.

[6] Fortunately, stabilization scenarios are not the only options available: indeed, the chances of future generations maintaining a specified concentration of CO_2 indefinitely are probably very small. Other properties of the climate system are much better constrained by observations: for example, the normalized transient climate response (NTCR) which we define as the rate of warming in degrees per year divided by the fractional rate of CO_2 increase per year. It has units K and, if we focus on long-term gradual forcing changes the NTCR, is approximately independent of forcing. This allows comparison between studies (in much the same way as "effective" climate sensitivity does), although a specific definition is clearly needed for model intercomparisons. This could remain based on the traditional definition of 70 year warming on a 1% per annum increase in CO_2, simply expressed in degrees per century, allowing for direct comparisons with TCR. Note that NTCR is very simply related to traditional TCR, such that NTCR = TCR/0.7. Figure 2 shows 20th century warming attributable to greenhouse gases [*Stott and Kettleborough*, 2002; *Stott et al.*, 2006] versus NTCR for our observationally-constrained model ensemble. It shows that there is quite a tight relationship between the two, demonstrating that, unlike in the case of climate sensitivity, uncertainties in (observed) attributable warming scale roughly linearly in the forecast variable. This remains the case even when we depart from our recommended strategy for forming priors uniformly in the forecast variable: in the case where we predict NTCR with a prior uniform in *S*, purely for comparative purposes, we still find that NTCR is better constrained by the data than is equilibrium sensitivity: the distribution of NTCR with a uniform prior in NTCR has an upper bound (95%) of around 5.1°C; when we predict NTCR with a uniform prior in *S*, this upper bound inflates by around a quarter to 6.4°C. These distributions are shown on the vertical axis of Figure 2 as solid and dotted curves, respectively. The effect of the choice of prior is much greater in the case of *S* than it is for NTCR, as can be verified by comparing Figure 2 to Figure 1: when predicting *S*, choosing a prior which is uniform in *S* yields a distribution the 95% upper bound of which is more than twice as high as that obtained when predicting *S* using a prior that is uniform in NTCR. These results demonstrate that NTCR is better constrained than *S*, regardless of the choice of prior. Moreover, these results also show that predictions of *S* are far more sensitive to choice of prior than are predictions of things which scale more linearly with the observational data used in the forecast.

[7] NTCR turns out to be much more relevant than sensitivity for a scenario in which forcing reaches the equivalent of 550ppmv CO_2 (double pre-industrial, though the same point holds for higher and lower peak forcings) and then declines by 10% over the ensuing 40 years,

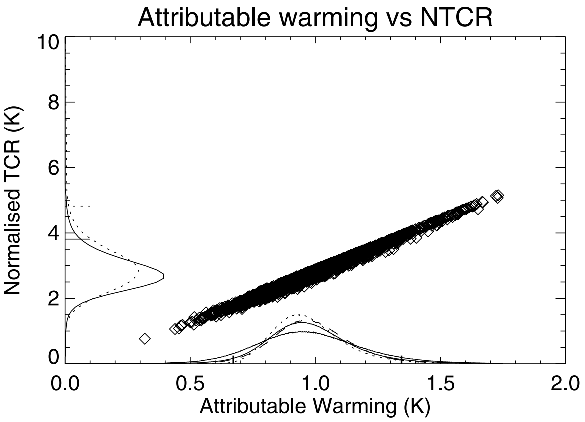

Figure 2. Relationship between the current rate of greenhouse gas-induced warming inferred from 20th century temperature changes and normalized transient climate response (NTCR), for an observationally constrained perturbed physics energy balance model ensemble following *Frame et al.* [2005]. Also shown are likelihood distributions for attributable warming from 3 models (HadCM3, solid curve; PCM; dotted curve; GFDL, dashed curve) and NTCR (distribution at left). The three model average (and associated 5–95% range) is shown as the heavier line on the bottom axis. The forecast distributions for NTCR using a uniform prior in the forecast variable (solid curve) and using a uniform prior in S (dotted curve) are shown, with associated 95% upper bounds, on the vertical axis.

continuing to decline thereafter. Given that emissions would have to decline from current levels by around a factor of two by 2100 to achieve 550ppm stabilization [*Nakicenovic et al.*, 2000], the additional reduction to achieve the necessary forcing profile for this scenario is perfectly sensible, subject to uncertainty in the carbon cycle. Recent explorations of "overshoot" scenarios [*O'Neill and Oppenheimer*, 2004; *Mastrandrea and Schneider*, 2005] have explored scenarios in which greenhouse gas concentrations peak sometime in the next century, before relaxing back to a considerably lower stabilization level. The scenario presented here is simply an extension of this idea, with a lower than usual stabilization level: in this case, CO_2 concentrations peak at 550ppmv in 2100 before eventually dropping back to near pre-industrial levels. The diamonds in Figure 3 show a transfer function between attributable warming (bottom axis) and the maximum warming under this scenario. It can be seen that this transfer function is much more linear and observationally well-constrained than the equivalent transfer function for sensitivity. Again, we show the effects of choosing a different prior (uniform in *S*) as a dotted curve on the vertical axis. As with NTCR, the difference between choosing a prior that is uniform in *S*, rather than choosing a prior uniform in the forecast variable, (spuriously) inflates the upper bound of the forecast distribution from 4.6°C to around 6.5°C. This scenario, and others possessing similar structure, provide a useful alternative to stabilization scenarios, particularly on timescales out to about a few hundred years. The basic problem with sensitivity is that high sensitivities take a long time to come into equilibrium. This requires that forcings remain constant (or very nearly so) for a long time, possibly hundreds of years. This seems environmentally and economically unlikely.

[8] Any stabilization scenario involves a leveling off in the rate of emission reduction as stabilization approaches [*Wigley et al.*, 1996]. In the sort of alternative scenario described above such a decline would not necessarily be substantially harder than stabilization since it really only requires postponing the point at which emissions level off. In our alternative scenario emission reduction rates can be the same as in the stabilization case but need to be maintained for over a longer period of time. The concentrations return to near pre-industrial levels, and the eventual long-term carbon concentration is sufficiently close to pre-industrial levels that carbon cycle uncertainty dominates the uncertainty in the stabilization level. Given the considerable uncertainties surrounding the carbon cycle [*Plattner et al.*, 2001; *Kheshgi and Jain*, 2003], which only grow over time, it does not seem unreasonable to assume that the carbon cycle uncertainties dominate our knowledge of the stabilization level on timescales of more than a couple of hundred years.

[9] Maximum warming under a scenario in which CO_2 levels peak and then decline is relatively well constrained by observations because it is closely proportional to the NTCR. There is a much higher level of consensus regarding the NTCR than *S*, because NTCR is directly related to the current rate of greenhouse warming [*Frame et al.*, 2005; *Stott and Kettleborough*, 2002]: the estimates of NTCR presented here are consistent with the standard IPCC range,

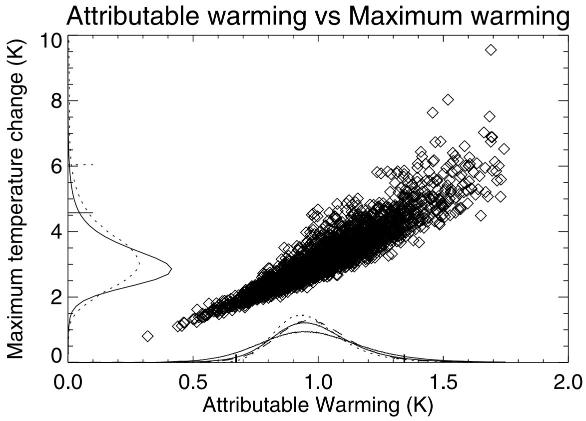

Figure 3. Relationship between the current rate of greenhouse gas-induced warming inferred from 20th century temperature changes and maximum warming under a scenario in which CO_2 concentrations peak in 2100 and decline by 10% by 2140, continuing to decline thereafter. As in Figures 1 and 2 the diamonds represent the members of an observationally constrained perturbed physics energy balance model ensemble following *Frame et al.* [2005]. Also shown are likelihood distributions for attributable warming from 3 models (HadCM3, solid curve; PCM; dotted curve; GFDL, dashed curve) and maximum warming under this scenario (distribution at left). The three model average (and associated 5–95% range) is shown as the heavier line on the bottom axis. The forecast distributions for maximum warming using a uniform prior in the forecast variable (solid curve) and using a uniform prior in *S* (dotted curve) are shown, with associated 95% upper bounds, on the vertical axis.

the range obtained under 0.55%/year increasing CO_2 (after *Hansen and Sato* [2001] and *Michaels and Balling* [2000]) and the range given by a recent attempt to estimate TCR "probabilistically" from a perturbed-physics ensemble experiment [*Collins et al.*, 2005]. The agreement between these three sources is remarkably good given their very different starting points and approaches.

4. Discussion

[10] These results are insensitive to the precise rate of decline in CO_2 concentrations, provided CO_2 eventually reverts to near-pre-industrial levels as fossil fuels are phased out over the coming centuries. Under such a containment scenario we see a much more linear relationship between past and maximum future warming, providing a more robust constraint.

[11] Given the difficulties in determining climate sensitivity, we suggest that the climate policy community might begin to consider whether the UNFCCC should be interpreted a little differently. Since the ultimate objective of the Convention is to avoid dangerous climate change, and the commitment to stabilize future greenhouse gas concentrations does not preclude stabilization at near pre-industrial levels, "stabilize" could be interpreted simply as "bring back down" rather than as "freeze at a given elevated concentration in perpetuity", particularly since this second interpretation is both economically and environmentally implausible. For many purposes, and especially for much policy work, it ought to prove both more appropriate to focus on peak warming under transient and containment scenarios than to focus on poorly constrained scenarios under which greenhouse gas concentrations stabilize indefinitely at an elevated level. While equilibrium climate sensitivity and associated stabilization scenarios remain mired in scientific uncertainty, policies focusing on peak warming under a containment scenario can already draw on a relatively high level of scientific consensus on TCR. Addressing containment scenarios such as the one developed above may provide a means of refocusing our efforts away from the difficult goal of constraining equilibrium climate sensitivity onto the much more achievable and often more policy-relevant goal of consolidating consensus on the TCR and its variants, at both global and regional levels.

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