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What do recent advances in quantifying climate and carbon cycle uncertainties mean for climate policy?

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Abstract
Global policy targets for greenhouse gas emissions reductions are being negotiated. The amount of emitted carbon dioxide remaining in the atmosphere is controlled by carbon cycle processes in the ocean and on land. These processes are themselves affected by climate. The resulting 'climate–carbon cycle feedback' has recently been quantified, but the policy implications have not. Using a scheme to emulate the range of state-of-the-art model results for climate feedback strength, including the modelled range of climate sensitivity and other key uncertainties, we analyse recent global targets. The G8 target of a 50% cut in emissions by 2050 leaves CO_2 concentrations rising rapidly, approaching 1000 ppm by 2300. The Stern Review's proposed 25% cut in emissions by 2050, continuing to an 80% cut, does in fact approach stabilization of CO_2 concentration on a policy-relevant (century) timescale, with most models projecting concentrations between 500 and 600 ppm by 2100. However concentrations continue to rise gradually. Long-term stabilization at 550 ppm CO_2 requires cuts in emissions of 81 to 90% by 2300, and more beyond as a portion of the CO_2 emitted persists for centuries to millennia. Reductions of other greenhouse gases cannot compensate for the long-term effects of emitting CO_2.

Keywords: carbon dioxide, climate, policy, carbon cycle, feedbacks, uncertainty, Stern Review, emissions targets, stabilisation

1. Introduction: climate policy

The temperature increase due to human activity since pre-industrial times has been in the order of 0.8 °C (IPCC 2007). The Intergovernmental Panel on Climate Change (2007) projected an additional global warming of 1.1–6.4 °C for the 21st century based on greenhouse gas emissions scenarios (SRES) that intentionally exclude mitigation policy (Nakićenović and Swart 2000). The United Nations Framework Convention on Climate Change commits its signatories to achieve '… *stabilization of greenhouse gas concentrations in the atmosphere at a level that would*

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prevent dangerous anthropogenic interference with the climate system'. What constitutes 'dangerous' climate change is difficult to determine and highly subjective as regional impacts, rate of change and ability to cope with change are highly variable (Schellnhuber *et al* 2006). The EU has adopted a target of limiting global warming to 2 °C above pre-industrial levels (European Council 2007). Some argue that this may already be unachievable or undesirable due to the costs of mitigation. Nonetheless, efforts are being made to negotiate international targets to limit climate change.

The Kyoto Protocol set emissions reduction targets for industrialized countries based on what could be achieved politically, rather than what would be needed for a desired outcome (Prins and Rayner 2007). While continuing negotiations seek to strengthen and extend the scope of Kyoto, several countries and organizations have formulated aspirational global greenhouse gas emissions goals (Weaver *et al* 2007). The powerful G8 (Group of 8)[6] nations in 2007 issued a non-binding aim '*to at least half global emissions of* CO_2 *by 2050*' (G8 2007); they did not specify what the ultimate goal was in terms of concentration or climate, or what should happen after 2050.

The Stern Review (Stern 2006) is more explicit, stating that '*The risks of the worst impacts of climate change can be substantially reduced if greenhouse gas levels in the atmosphere can be stabilized between 450 and 550 ppm* CO_2 *equivalent. Stabilization in this range would require emissions to be at least 25% below current levels by 2050, and perhaps much more. Ultimately, stabilisation—at whatever level—requires that annual emissions be brought down to more than 80% below current levels.*' The emissions reductions required to achieve these levels of stabilized concentration were derived from results in the IPCC Third Assessment Report in 2001 (Prentice *et al* 2001). While the 2001 model results incorporated ranges due to uncertainty in carbon cycle processes, climate sensitivity to CO_2 and climate impacts on the carbon cycle, models have since been updated and in particular there has been more explicit quantification of the feedbacks between the carbon cycle and climate. The modelled effect of climate–carbon cycle feedbacks imply substantially greater impacts for a given emissions trajectory, or lower allowable emissions to meet a given concentration or temperature target (Cox *et al* 2000, Matthews 2006, Friedlingstein *et al* 2006, Jones *et al* 2006a, 2006b, Plattner *et al* 2006). This paper explores the implications for the G8 and Stern emissions targets in terms of concentration and temperature change, spanning the range of uncertainty across state-of-the-art models. It also explores the implications for allowable emissions to achieve stabilization of atmospheric CO_2 at 550 ppm.

2. Carbon dioxide and long-term climate impacts

In this analysis we focus on carbon dioxide. CO_2 currently accounts for about two thirds of the radiative forcing produced by all greenhouse gases (IPCC 2007). The contribution of other GHGs has commonly been expressed in terms of 'CO_2 equivalent' concentrations and emissions. In the latter case this means emissions are scaled relative to CO_2 according to their global warming potential over a given time horizon (commonly 100 years). However, this equivalence is not meaningful at other timescales because as much as a third of all CO_2 emitted remains in the atmosphere for thousands to tens of thousands of years; while the next most radiatively important greenhouse gasses are removed over much shorter time periods (e.g. 12 years for methane, 114 years for nitrous oxide) (Archer *et al* 1997, Archer 2005, Denman *et al* 2007, Forster *et al* 2007). Thus in the near term, manipulation of other greenhouse gases such as methane can influence the pathway of global warming, but in the long term it is the *accumulated* emissions of CO_2 that count (Matthews 2006, Meinshausen *et al* 2006, Denman *et al* 2007, den Elzen *et al* 2007).

The long-term legacy of CO_2 emissions is compounded by inertia in the climate system. Due to the mass and thermal capacity of the oceans and ice, and the slowness of heat transport processes, it takes a long time for the atmospheric temperature to fully respond to changes in radiative forcing. If CO_2 concentrations were stabilized on a timescale of 100 or so years, temperatures would still take several centuries to stabilize, sea level rise due to thermal expansion would take centuries to millennia, and sea level rise due to ice melting would take millennia (IPCC 2001). By contrast, climate policy typically considers climate impacts and mitigation targets on the timescale of decades up to a century.

3. The carbon cycle, feedbacks and scientific uncertainty

Less than half of the total cumulative anthropogenic CO_2 emitted due to fossil fuel burning and land use change (deforestation) has remained in the atmosphere, the rest has been taken up by the land and ocean (Prentice *et al* 2001). The major land and ocean carbon sinks active today are responsive to the raised atmospheric CO_2 levels. The ocean sink occurs due to the partial pressure difference of CO_2 between the atmosphere and ocean. CO_2 dissolves in the ocean surface waters and ocean circulation transfers it to depth. Plants take up CO_2 during photosynthesis and convert it into biomass. Plants release CO_2 during plant (autotrophic) respiration and decay (heterotrophic respiration). Raised concentrations of CO_2 stimulate additional growth in terrestrial plants (CO_2 fertilization effect), drawing down CO_2 from the atmosphere in a negative carbon cycle feedback (Prentice *et al* 2001, Norby *et al* 2005). The magnitude and long-term persistence of the CO_2 fertilization effect is uncertain, and differs in model projections (Friedlingstein *et al* 2006, Plattner *et al* 2006, Sitch *et al* 2008). Note that since increasing CO_2 levels stimulate CO_2 uptake in the ocean and on land, these sinks will continue to operate as long as atmospheric CO_2 concentration is rising and the land sink does not saturate. However, these sinks must both tend to zero as a stable CO_2 concentration is approached.

The land and ocean carbon sinks are also sensitive to climate change. Warming reduces the solubility of CO_2

[6] The Group of Eight (G8) is an international forum for the governments of Canada, France, Germany, Italy, Japan, Russia, the United Kingdom, The United States and the European Union.

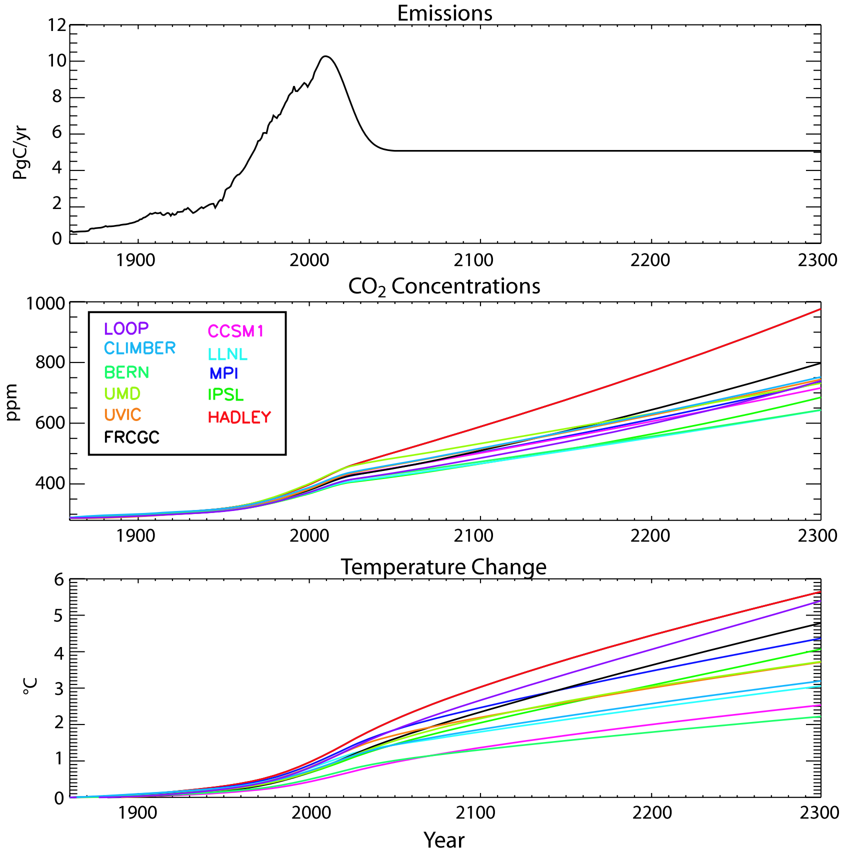

Figure 1. Implications of the 'G8 scenario' 50% global emissions reduction: the top panel shows historical and future emissions. Historical emissions of CO_2 are from fossil fuel burning, plus net emissions from land use change (Houghton 2003). It is assumed that future emissions rise for a short time and are then cut until the target of 50% reductions by 2050 is reached (relative to 2007 emissions, assumed to be 10.15 Pg C yr^{-1}), with emissions maintained at this level thereafter. The middle and bottom panels show the resulting changes in concentrations and temperature respectively according to HadSCCM1 box model, tuned to each of the eleven different C^4MIP coupled climate–carbon cycle models.

in the ocean, reducing ocean uptake (positive feedback). Increasing temperatures are also likely to cause vertical stratification in the ocean, reducing transport to the deep ocean (positive feedback), and affecting biological productivity (sign of feedback uncertain). On land, warming increases the rate of heterotrophic respiration (positive feedback) (Prentice *et al* 2001, Knorr *et al* 2005). Changes in temperature and precipitation will have regionally specific effects on plant growth. For example, increasing plant growth due to longer growing seasons in northern high latitudes for moderate temperature increases (negative feedback), and reducing growth due to heat stress and drought in low to mid-latitude regions (positive feedback). Many models have indicated a net positive 'climate–carbon cycle feedback' such that global warming drives a reduction in net CO_2 uptake (e.g. Cox *et al* 2000, Friedlingstein *et al* 2006, Plattner *et al* 2006, Sitch *et al* 2008). While the magnitude of this feedback varied considerably between studies, some indicated a very large effect that would have major implications for projecting climate change impacts, or indeed for calculating the level of anthropogenic emissions consistent with achieving stabilization targets.

Eleven state-of-art global climate models that participated in the IPCC (2007) assessment were coupled to carbon cycle models to study the magnitude of the climate–carbon cycle feedbacks in the Coupled Climate–Carbon Cycle Model Intercomparison Project (C^4MIP) (Friedlingstein *et al* 2006). These models incorporated a range of climate sensitivities[7], one of the key uncertainties in climate modelling (Knutti *et al* 2008). The models represent a range of CO_2 fertilization strengths and other differences in carbon cycle processes reflecting uncertainty in the state of knowledge. Simulations were made with the climate response incorporated, and then suppressed, to isolate the responses of the modelled ocean and land carbon sinks to CO_2 increases alone. Under a particular CO_2 emissions scenario (IPCC SRES A2) (Nakićenović and Swart 2000), projected atmospheric concentration at 2100 was greater by 20–225 ppm relative to simulations without climate–carbon cycle feedback. This range equates to an additional temperature increase of 0.1–1.5 °C (Friedlingstein *et al* 2006). None of the models included in the C^4MIP analysis combined high climate sensitivity with high climate–carbon cycle feedbacks, which would imply even greater warming.

[7] Climate sensitivity refers to the change in the annual mean global surface temperature for a given change in radiative forcing, usually referenced to the equilibrium change projected for a doubling of atmospheric CO_2 concentration. It is a major uncertainty in future climate projections.

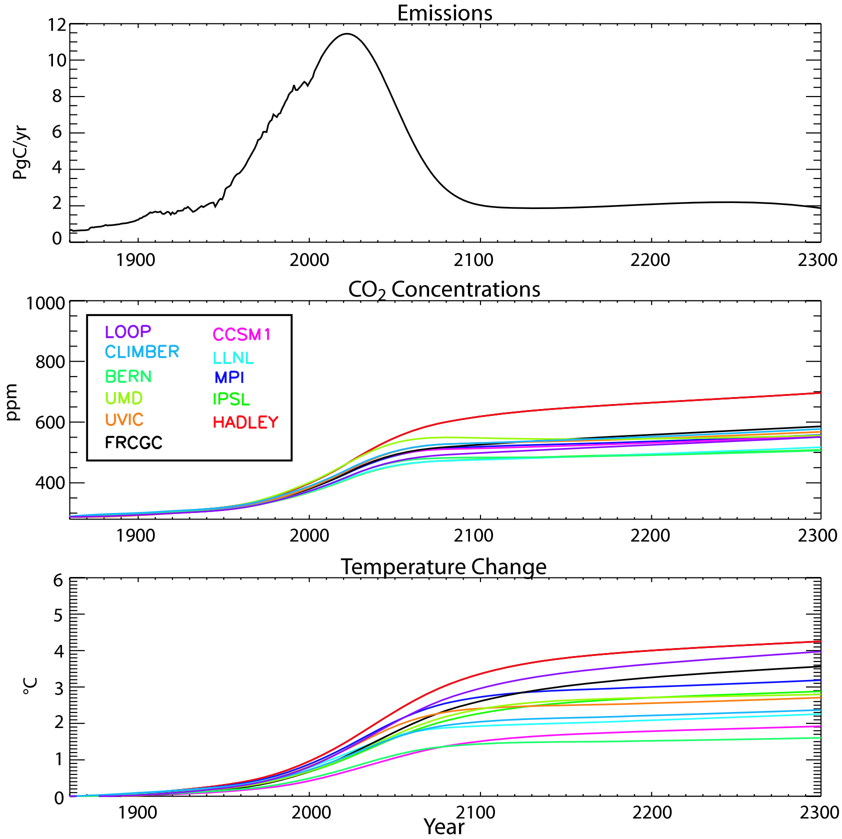

Figure 2. Implications of the 'Stern scenario 80% global emissions reduction: the top panel shows historical emissions as in figure 1. It is assumed that future emissions rise for a short time and are then cut until the target of 25% reductions by 2050 is reached (only half the G8 Commitment), but then continuing at the same rate of decline until 80% cuts (relative to 2007) are achieved. Peak emissions are later and higher, and the rate of subsequent reductions is slower, than in the G8 scenario.

4. Methods summary

In the present analysis, a simple coupled climate–carbon cycle model HadSCCM1 (Jones *et al* 2006a) was calibrated so as to emulate both the carbon cycle responses to climate and the climate sensitivity for the 11 fully coupled models participating in C^{4}MIP. We used global-mean outputs from these simulations to calibrate the simple model for each of the coupled models. (For more information see the appendix.)

CO_2 emissions profiles were defined that provide a smooth transition to the G8 and Stern emissions reductions targets. Results are not strongly sensitive to the detailed time course of the emissions cuts (Jones *et al* 2006b, Matthews 2006).

5. Results

The 'G8 scenario' (figure 1) cuts current (2007) global emissions by 50% by 2050, with emissions then held constant at this target level. Atmospheric CO_2 concentration continues to increase after 2050. By 2100 the CO_2 concentration is 470 to 590 ppm and the global-mean temperature is 1.3–3.1 °C above pre-industrial levels. By 2300 CO_2 concentration has risen as high as 640–980 ppm, temperature has risen by 2.2–5.7 °C and both continue to rise rapidly thereafter.

The 'Stern scenario' (figure 2) cuts emissions by 25% by 2050, with progressive cuts thereafter, down to 80%. CO_2 concentrations in 2100 reach 480–620 ppm with a corresponding temperature change of 1.4–3.4 °C. These 2100 levels are slightly higher than the 'G8 scenario' as emission reductions happen more slowly, showing that cutting early can be as important as cutting deeply for nearer term impacts. Nevertheless, once the final target of 80% has been achieved, the CO_2 concentration increase after 2100 is slight, reaching 510–700 ppm by 2300 with temperature approaching, but not quite achieving, stabilization between 1.6 and 4.2 °C. Thus in the longer term it is the depth of cuts (or total cumulative emissions) that is more important (Matthews 2006).

When emissions are set initially to follow the G8 scenario with a 50% cut in emissions by 2050, but then continue on the same trajectory to reach an 80% cut (not shown), a warming of less than 2 °C in 2100 is shown by all models.

What mitigation action is necessary to achieve stabilization at 550 ppm (Stern's upper bound) when taking account of the climate–carbon cycle feedback and other uncertainty ranges across the C^{4}MIP models? Again using the simple model to emulate all 11 C^{4}MIP models, we calculated allowable emissions to achieve the IPCC WRE550 stabilization pathway (Wigley *et al* 1996). Our analyses show that by 2100, cuts of up to 80% are necessary. Most models actual allow a somewhat slower near-term decline in emissions than Stern proposes. The need for progressive emissions reductions in the long term however continues beyond 2100, with required cuts reaching 81–90% by 2300.

The results of the 550 ppm stabilization scenario runs are consistent with results of modelling sensitivity studies that varied the size of the climate–carbon cycle feedback, climate sensitivity and other carbon cycle processes within models (Matthews 2006, Jones *et al* 2006b, Plattner *et al* 2006). These studies found substantial variation due to both the carbon cycle (e.g. CO_2 fertilization) and climate sensitivity (which compounds climate–carbon cycle feedback uncertainty). The results that the permissible emissions to achieve stabilization must be substantially reduced when climate–carbon cycle feedbacks are included, and that to achieve stabilization at any level emissions must be substantially below present levels, are robust across a range of models and model settings. The range across model emulations is similar to the ranges obtained by changing sensitivities to processes within models (Plattner *et al* 2006). Using simplified models tuned to reproduce the behaviour of more comprehensive, computationally intensive, carbon cycle and climate models is a robust tool for exploring a range of emissions scenarios and climate projections spanning the range of model variability.

6. Conclusions

On the timescale of decades to a century (the more common domain of climate-based policy making), Stern's proposal of 80% emissions cuts remains an effective near-term target on the pathway to achieve stabilization of CO_2 concentrations or climate. This conclusion is robust despite the large uncertainty in the climate–carbon cycle feedback. Ultimately, however, climate stabilization at any level can only be achieved if net global CO_2 emissions decline over centuries to the level of persistent natural sinks ($\ll$1 Pg C yr^{-1}, or just a few % of today's emissions) (Archer *et al* 1997, Prentice *et al* 2001, Caldeira *et al* 2003, Archer 2005, Lenton *et al* 2006, Denman *et al* 2007, Tyrrell *et al* 2007). On the timescale of centuries to millennia, over which the impacts of today's CO_2 emissions are still being felt, stabilization in the presence of a non-trivial anthropogenic source of CO_2 is only possible if this source is balanced by an artificial sink (Haugen and Eide 1996, Prentice *et al* 2001, Weaver *et al* 2007). The long-term impact of today's emissions brings this planetary timescale into contemporary policy relevance.

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Appendix. Detailed methods

The calibration of the land component of the box model Hadsccm1 followed Jones *et al* (2006b) with one extension: vegetation and soil carbon turnover rates now include linear dependence on the size of their respective carbon pools. The initial values of these global-mean vegetation and soil carbon pools, as diagnosed from the C^4MIP runs, were prescribed as part of the calibration. The half-saturation constant for land net primary productivity (NPP) as a function of ambient CO_2 concentration was estimated from the C^4MIP runs without carbon cycle feedback. Then the climate sensitivities of NPP and soil respiration could be derived from the fully coupled simulations: equations (1)–(3) of Jones *et al* (2006b). Oceanic drawdown of CO_2 was modelled using the impulse–response approach of Joos *et al* (1996), with the depth of the mixed layer fitted to reproduce the trajectory of the ocean carbon sink in each of the C^4MIP models (see appendix of Huntingford *et al* 2004). Global warming due to CO_2 increase was defined in terms of an equilibrium climate sensitivity, T_{2CO2} and oceanic thermal capacity c_p. T_{2CO2} was estimated by calibration against C^4MIP model outputs, except for the UMD model where the warming constraint was not sufficient to yield a single well-defined value and a value was adopted from the published literature.

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