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Emissions targets for CO_2 stabilization as modified by carbon cycle feedbacks

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ABSTRACT

Carbon cycle feedbacks will have a direct effect on anthropogenic emissions required to stabilize CO_2 in the atmosphere. In this study, I used an intermediate complexity coupled climate-carbon model to quantify allowable CO_2 emissions for a series of scenarios leading to CO_2 stabilization at levels between 350 and 1000 ppmv. For all scenarios, global temperature did not stabilize over the next several centuries, but rather continued to increase well beyond the point of CO_2 stabilization. Furthermore, neither long-term climate change, nor total allowable CO_2 emissions, were sensitive to the shape of the CO_2 stabilization profile, but only to the final stabilization level. For the 550-stabilization scenario, positive carbon cycle-climate feedbacks required a reduction of annual CO_2 emissions throughout the simulation, with a maximum reduction of 2.3 GtC/yr occurring at 2050. Total emissions over the 21st century were 20% lower than those derived from an equivalent simulation without feedbacks. In two additional runs with varied climate sensitivities, emissions consistent with 550-stabilization were reduced by between 190 and 540 GtC over the next 400 yr relative to the no-feedbacks run. Allowable emissions were further reduced in all cases if CO_2 increases did not affect future vegetation productivity, as this removed an otherwise important negative feedback on atmospheric CO_2.

1. Introduction

The carbon cycle is an integral component of the global climate system. The rate of accumulation of anthropogenic CO_2 in the atmosphere is critically dependent on the existence of terrestrial and oceanic carbon sinks. Over the past two centuries, less than half of emitted fossil carbon has remained in the atmosphere, the rest having been sequestered by the global carbon cycle (Prentice et al., 2001). A central question of carbon cycle research is the extent to which current carbon sinks will persist in the context of future anthropogenic climate changes.

The behaviour of the coupled climate-carbon system is central to determining how fast CO_2 will accumulate in the atmosphere in response to scenarios of anthropogenic emissions. Correspondingly, changes in the climate-carbon system will determine the extent of emissions reductions that are required to stabilize future levels of atmospheric CO_2. A weakening of terrestrial or oceanic carbon sinks in the future would reduce the ability of the carbon cycle to sequester anthropogenic carbon, and consequently would require lower levels of anthropogenic emissions in order to achieve a given stabilization target. Conversely, if carbon sinks strengthen in the future, allowable emissions consistent with stabilization would be higher. The potential for both positive and negative feedbacks between climate, atmospheric CO_2 and the carbon cycle is paramount in any discussion of anthropogenic CO_2 emissions reductions that are required in order to achieve CO_2 stabilization.

Stabilization of atmospheric CO_2 is a key target set out in the United Nations Framework Convention on Climate Change (United Nations, 1992). As stated in Article 2, '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'. Following this statement, a number of CO_2 concentration scenarios have been developed that lead to the stabilization of atmospheric CO_2 at levels from 350 to 1000 ppmv over the next two centuries (Enting et al., 1994; Houghton et al., 1995; Wigley et al., 1996).

The anthropogenic CO_2 emissions scenarios consistent with these stabilization profiles were initially calculated using simplified models of the climate-carbon cycle system, which did not include climate feedbacks to ocean circulation or terrestrial ecosystem processes (Schimel et al., 1997). The effects of ocean circulation and carbon cycle changes have since been investigated using the Bern2.5D model (Joos et al., 1999), who showed that changes in ocean biology and circulation could both reduce stabilizing CO_2 emissions. The Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report (Prentice et al., 2001) further included an estimate of the terrestrial carbon cycle

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uncertainty in emissions projections, generated using simplified models tuned to reproduce the behaviour of more comprehensive carbon cycle and climate models (Joos et al., 2001; Kheshgi and Jain, 2003). These investigations showed that carbon cycle uncertainties increased the range of allowable emissions for CO_2 stabilization, emphasizing the strong coupling of the carbon cycle and climate systems and the importance of representing this relationship in future climate model projections.

The recent development of more comprehensive coupled climate-carbon models has enabled a coherent investigation of carbon cycle feedbacks at a global scale. Numerous studies have demonstrated the potential for positive feedbacks of varying strength between climate change and the carbon cycle (Cox et al., 2000; Friedlingstein et al., 2001; Dufresne et al., 2002; Jones et al., 2003; Thompson et al., 2004; Zeng et al., 2004; Fung et al., 2005; Govindasamy et al., 2005; Matthews et al., 2005a,b). Despite large variability between models in the strength of and mechanisms driving these positive feedbacks, all these studies have shown that atmospheric CO_2 at the year 2100 is higher when climate and the carbon cycle are coupled, due to a negative effect of climate changes on both terrestrial and oceanic carbon sinks. The conclusion that the net global carbon cycle-climate feedback is positive, is robust across the current generation of carbon-climate models, as well as across previously applied models of reduced complexity (Friedlingstein et al., 2006). Framed in the context of achieving CO_2 stabilization, this conclusion implies that emissions targets for stabilization will need to be reduced in order to accommodate the potential for positive carbon cycle-climate feedbacks.

The current generation of climate-carbon models also simulates large negative feedbacks between atmospheric CO_2 growth and the carbon cycle, whereby increased atmospheric CO_2 leads directly to stronger carbon sinks, and a consequently reduced rate of atmospheric CO_2 accumulation. In the ocean, increased atmospheric CO_2 drives increased oceanic carbon uptake as a result of an increased CO_2 concentration gradient at the ocean surface. In the terrestrial biosphere, increased atmospheric CO_2 has the potential to stimulate photosynthesis (CO_2 fertilization) with the result that terrestrial carbon sinks strengthen in response to rising atmospheric CO_2 (Prentice et al., 2001). Both of these negative carbon cycle feedbacks imply that emissions targets for stabilization can be set higher than would be the case in the absence of these feedbacks. However, there is currently large uncertainty with respect to the actual efficacy of CO_2 fertilization with respect to stimulating carbon uptake in real ecosystems (e.g. Caspersen et al., 2000; Schimel et al., 2001; Joos et al., 2002; DeLucia et al., 2005; Vetter et al., 2005). If other limiting factors on photosynthesis, such as nitrogen availability (Oren et al., 2001), prevent substantial CO_2 fertilization in the future, emission targets will have to be reduced considerably in order to accommodate a dramatically reduced terrestrial carbon sink.

In this study, I have used an intermediate complexity climate-carbon model to quantify the potential for carbon cycle feedbacks to affect emissions targets for CO_2 stabilization. Previous studies using comprehensive climate-carbon models have explored in detail the effect of carbon cycle feedbacks on atmospheric CO_2 growth over the next century (e.g. Friedlingstein et al., 2006); to date, the effect of these feedbacks on emissions targets for stabilization over the next several centuries has received only limited attention. In this paper, I have calculated emissions for a series of CO_2 stabilization runs, with stabilization levels varying from 350 to 1000 ppmv. I focus on the effect of carbon cycle feedbacks over the next 100 to 400 yr in a scenario of CO_2 stabilization at 550 ppmv; the reader is referred to (Matthews, 2005) for a discussion of the effect of carbon cycle-climate feedbacks on emissions targets in the context of a 1000-year simulation of CO_2 stabilization at 1000 ppmv, as well as to (Jones et al., 2006a) for discussion of allowable emissions from the HadCM3LC climate model and to (Jones et al., 2006b, this issue) for a sensitivity study of allowable emissions using a simple analogue climate-carbon cycle model. The current study goes beyond the scope of Matthews (2005) by looking at both a suite of possible stabilization scenarios, as well as the effect of variability in both climate sensitivity and the strength of future CO_2 fertilization. Furthermore, the shorter time frame discussed in the current study reflects the importance of decisions made in the coming decades in affecting the evolution of the climate system over the next several centuries.

2. Methods

2.1. Model description

The coupled climate-carbon model used here is the University of Victoria Earth System Climate Model (UVic ESCM) version 2.7. The climate component of the UVic ESCM is comprised of a three-dimensional ocean general circulation model coupled to a dynamic-thermodynamic sea-ice model and energy-moisture balance atmosphere (Weaver et al., 2001). The ocean carbon cycle simulates ocean-atmosphere carbon fluxes and the passive transport of inorganic carbon based on the OCMIP abiotic protocol (Orr et al., 1999; Ewen et al., 2004). The terrestrial carbon cycle is a spatially explicit biochemical vegetation model taken from the Hadley Centre land surface (MOSES2; Cox et al., 1999; Essery et al., 2003) and dynamic vegetation (TRIFFID; Cox, 2001) models. MOSES/TRIFFID simulate the spatial distribution and carbon content of five plant functional types (broadleaf and needleleaf trees, C_3 and C_4 grasses, shrubs) as a function of climate conditions and atmospheric CO_2. Agricultural areas are specified at year 1850 values by excluding the growth of tree and shrub plant types; this spatial distribution is held constant throughout the simulation, though within agricultural areas, grass plant types respond to changes in climate and CO_2 in an equivalent manner to areas of natural vegetation. As with many terrestrial carbon cycle models, gross primary productivity in MOSES2/TRIFFID increases as a function of elevated CO_2, in a

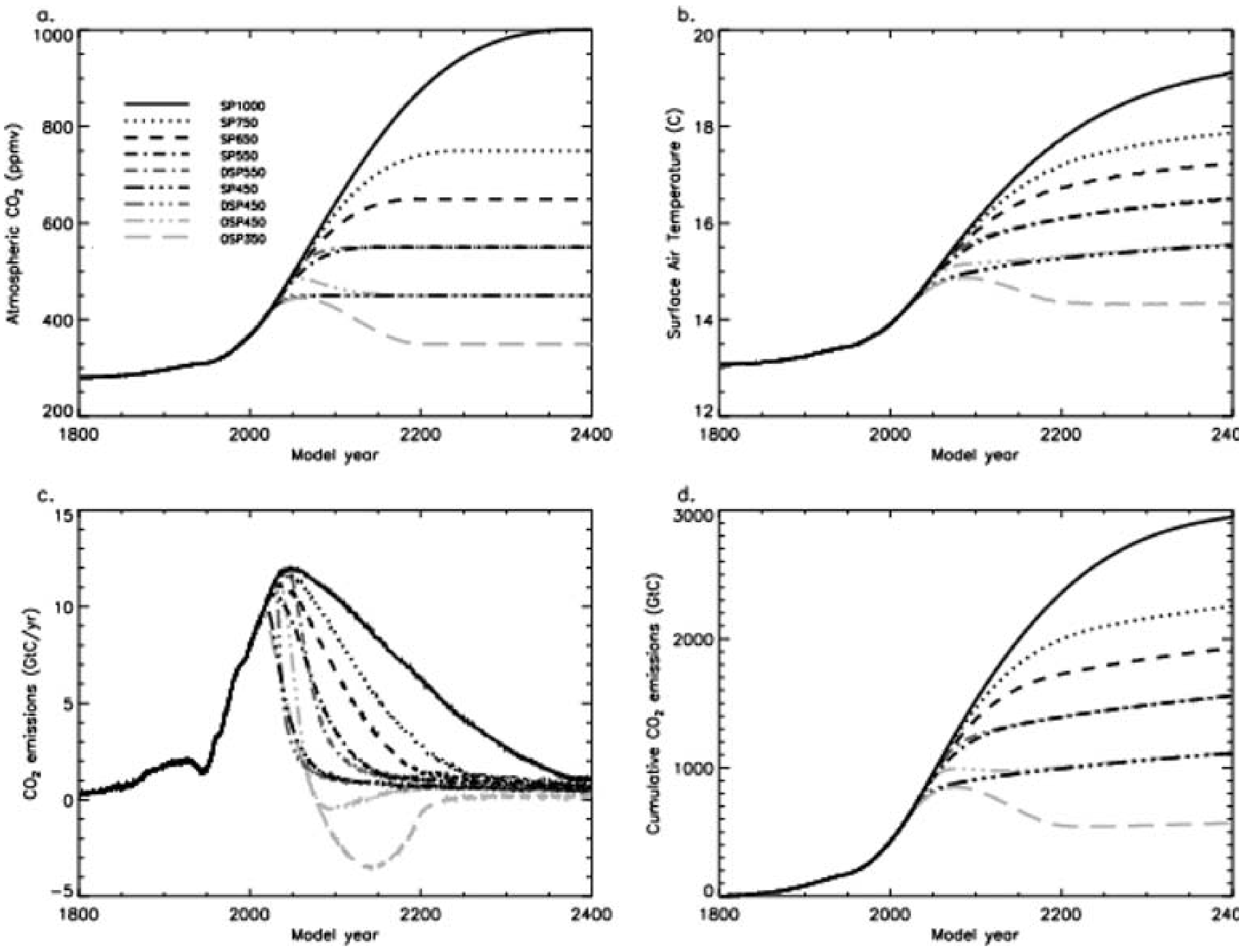

Fig. 1. Results from nine CO_2 stabilization scenario runs: (a) prescribed atmospheric CO_2; (b) modelled global mean surface air temperature; (c) calculated annual CO_2 emissions and (d) calculated cumulative CO_2 emissions.

manner consistent with other biochemical photosynthesis models (Adams et al., 2004). Carbon fluxes between the atmosphere and terrestrial biosphere are simulated as the difference between plant photosynthesis, and the sum of plant and soil respiration. The model has spatial resolution of 1.8 degree latitude by 3.6 degree longitude, and conserves energy, moisture and carbon to machine precision without the use of flux adjustments. This model has been described and validated extensively elsewhere, and the reader is referred to Weaver et al. (2001), Meissner et al. (2003) and Matthews et al. (2005b) for further details about the climate vegetation, and carbon cycle components of the model.

2.2. Experimental design

In this study, I have made use of a series of scenarios of carbon dioxide concentrations that stabilize at levels between 350 and 1000 ppmv over the next 50 to 350 yr. These stabilization profiles (SP scenarios) have been developed in the context of the IPCC Fourth Assessment Report, and are available from www.climate.unibe.ch/emicAR4. Scenarios SP450, SP550, SP650, SP750 and SP1000 are each comprised of observed carbon dioxide concentrations from 1765 to 2004, followed by a splined increase to stabilization (Enting et al., 1994) at levels from 450 to 1000 ppmv, respectively. Scenarios DSP450 and DSP550 represent “delayed” turning point scenarios, which achieve the same stabilization level, but via a different trajectory than the corresponding SP450 and SP550 scenarios. Scenarios OSP350 and OSP450 represent profiles that overshoot the stabilization target, and subsequently follow a decreasing CO_2 trend to stabilization (Knutti et al., 2005).

The nine scenarios described above are shown in Fig. 1a. Each of these scenarios have been used to force the UVic ESCM from 1765 to the year 2400. From these prescribed-CO_2 experiments, anthropogenic emissions of carbon dioxide can be calculated as the sum of prescribed atmospheric CO_2 increases (ΔC_A) and simulated changes in land (ΔC_L) and ocean (ΔC_O) carbon storage:

$$E(t) = \Delta C_A + \Delta C_L + \Delta C_O. \tag{1}$$

Table 1. Simulations performed forced by the SP550 scenario

Run	Description (Climate Sensitivity)
CS0	Uncoupled-climate run (~0 °C)
CS2.6	Low climate sensitivity run (2.6 °C)
CS4.2	Standard coupled run (4.2 °)
CS5.4	High climate sensitivity run (5.4 °)
CS0NF	As CS0, but with no CO_2 fertilization after 2000
CS2.6NF	As CS2.6, but with no CO_2 fertilization after 2000
CS4.2NF	As CS4.2, but with no CO_2 fertilization after 2000
CS5.4NF	As CS5.4, but with no CO_2 fertilization after 2000

Since carbon is conserved in the model, $E(t)$ represents the anthropogenic CO_2 emissions that are required in order to achieve stabilization of carbon dioxide in the atmosphere.

To examine the effect of carbon cycle feedbacks, I performed additional simulations, focusing on the SP550 stabilization scenario. The eight simulations performed using this scenario are listed and described in Table 1. The effect of carbon cycle-climate feedbacks can be isolated by performing a simulation in which the direct greenhouse effect of increasing atmospheric CO_2 is removed from the model; in this simulation climate is maintained at pre-industrial levels, and the carbon cycle responds to atmospheric CO_2 increases in the absence of any feedbacks between climate change and the carbon cycle. Comparing this 'uncoupled-climate' simulation (run CS0 in Table 1) to an equivalent climate change ('coupled') simulation gives an estimate of the effect of positive carbon cycle-climate feedbacks on emissions required to stabilize atmospheric CO_2 at 550 ppmv. It is worth noting that climate change in the uncoupled-climate simulation are not zero due to dynamic vegetation (and consequent surface albedo) changes in response to elevated CO_2. However, the resultant climate warming is small relative to direct CO_2-induced climate change, and thus does not have a large effect on the coupled-uncoupled differences presented in the next section.

In addition to the standard model coupled run, I have performed two additional simulations with increased and decreased equilibrium climate sensitivity (the climate warming response to doubled carbon dioxide). Several recent model studies have demonstrated that increasing climate sensitivity can have a strong effect on the magnitude of carbon cycle-climate feedbacks, resulting from larger climate changes, and the resultant larger effect of these climate changes on the strength of carbon sinks (Govindasamy et al., 2005; Matthews et al., 2005b; Friedlingstein et al., 2006). CO_2 forcing in the UVic ESCM (F) is parametrized according to a logarithmic forcing relationship, as:

$$F = F_0 \ln \frac{C_{(t)}}{C_0}, \qquad (2)$$

where F_0 is a constant in W/m^2, $C_{(t)}$ is the atmospheric CO_2 concentration at time t and C_0 is a reference CO_2 concentration (Weaver et al., 2001). For all simulations, the model was initialized to equilibrium (>2000 yr) with atmospheric CO_2 held fixed at 280 ppmv. CO_2 concentrations were then prescribed according the SP550 scenario, and the resultant forcing was calculated using eq. 2 and applied at each time step as a spatially uniform reduction of outgoing longwave radiation, consistent with the assumption of well-mixed atmospheric CO_2 in the UVic ESCM. In its standard configuration, the version of the UVic ESCM used here has a climate sensitivity of 4.2° (model run CS4.2 in Table 1).

By modifying the effective $C_{(t)}$ used in eq. 2, the forcing that results from increased CO_2 can be increased or decreased, with the result that the model's climate sensitivity can be varied. This is done by replacing eq. 2 with:

$$F = F_0 \ln \frac{C_{(t)} + k(C_{(t)} - 280.0)}{C_0}, \qquad (3)$$

where k is some constant greater than -1.0. Setting k equal to -0.6 and $+0.6$ resulted in climate sensitivities of 2.6 and 5.4° for doubled CO_2 in runs CS2.6 and CS5.4, respectively. It is worth noting here that this method has the equivalent effect to varying F_0, but without the requirement of re-initializing the equilibrium state of the model prior to initiating a transient simulation.

Also listed in Table 1 are four additional runs where CO_2 fertilization of terrestrial vegetation growth was fixed at pre-industrial levels. In its standard configuration, GPP in the UVic ESCM increases by about 35% in response to an instantaneous doubling of CO_2 from 280 to 560 ppmv. To remove this effect, I held CO_2 constant at year-2000 levels with respect to the terrestrial model, with the result that vegetation growth saw a constant atmospheric concentration of 367.3 ppmv from 2001 to 2400. This approach assumes that CO_2 fertilization can account for historical terrestrial carbon sinks, but that further elevation of CO_2 will not lead to increased future terrestrial carbon uptake. The four simulations described above were all repeated with CO_2 fertilization capped at present-day (CS0NF, CS2.6NF, CS4.2NF and CS5.4NF). Comparing each NF run with the equivalent CO_2-fertilized run gives an estimate of the effect of removing CO_2 fertilization as a contributor to future terrestrial carbon sinks on the emissions that are required to achieve the same stabilization target.

It is worth clarifying here that positive carbon cycle-climate feedbacks in these simulations include contributions from both the terrestrial and oceanic carbon cycles. In contrast, CO_2 fertilization is a negative feedback that involves the terrestrial carbon cycle only. An equivalent negative feedback operates in the ocean carbon cycle, whereby increased atmospheric CO_2 increases the concentration gradient across the air–sea interface, resulting in greater uptake of carbon by the inorganic ocean carbon cycle. However, there is much less uncertainty in strength of and processes that drive anthropogenic carbon uptake in the ocean (e.g. Sabine et al., 2004), and as such, the effect of this feedback is not quantified explicitly in this paper. For the sake of clarity, in this paper, I have used the term 'carbon cycle-climate feedbacks' to refer specifically to positive feedbacks between climate and the carbon cycle, whereas 'carbon cycle feedbacks' refers more generally to both positive and negative (e.g. CO_2 fertilization) feedbacks operating in the climate-carbon system.

3. Results

The results presented in this section are organized as follows: Section 3.1 presents results from all nine stabilization scenarios, showing how different stabilization targets and trajectories to stabilization affect the time-dependent and cumulative emissions that are required to achieve stabilization. Section 3.2 focuses on the SP550 scenario and the effect of carbon cycle feedbacks on emissions targets, showing results from the eight runs listed in Table 1. The effect of positive carbon cycle-climate feedbacks are presented in Section 3.2.1, with the effect of negative CO_2 fertilization feedbacks presented in Section 3.2.2.

3.1. All Stabilization Scenarios

Figure 1 shows results from the standard coupled model configuration, as forced by the nine CO_2 stabilization scenarios shown in Fig. 1(a). Figure 1(b) shows surface air temperature changes throughout the nine model runs; global temperature increases ranged from 0.4 °C (OSP350) to 5.2 °C (SP1000) between 2000 and 2400. It is notable here that stabilization of global temperature by the year 2400 did not follow from stabilization of atmospheric CO_2, due to the long thermal memory and equilibration time of the climate system. In all simulations, global temperature continued to rise after 2400, though in the case of OSP350, temperature increases beyond 2400 were very small (not shown). This result implies that stabilization of atmospheric CO_2 is not necessarily the best climate policy target, given that stabilization of 'climate' is of primary relevance to human societies. From these simulations, it is clear that climate stabilization over the next several centuries would require decreasing, rather than stabilized CO_2 concentrations.

It is also notable that the trajectory to stabilization over the next century is not relevant to longer term global temperature changes. In the case of CO_2 stabilization at 450 ppmv, three stabilization trajectories are represented here (SP450, DSP450 and OSP450). While there were small differences in simulated warming between these three simulations over the next century, beyond 2150, the global mean temperature changes of these three runs were virtually indistinguishable from each other. The implication here is that it is the final stabilization target, and not the pathway to stabilization, that determines the long-term climate changes that result from increased atmospheric CO_2. It should be noted, however, that this conclusion only holds in the absence of substantial non-linear climate responses to increasing CO_2 forcing. In the case of climate 'surprises'—such as a collapse of the Atlantic meridional overturning circulation, which may well be sensitive to the rate of atmospheric CO_2 growth (Stocker and Schmittner, 1997)—it is quite possible that long-term climate warming could depend on factors other than the final CO_2 stabilization target. Furthermore, it is possible that a larger range of stabilization scenario variants than those included here would reveal dependence of climate impacts on the specific stabilization trajectory (e.g. O'Neill and Oppenheimer, 2004).

Figures 1(c) and (d) show annual and cumulative anthropogenic CO_2 emissions, respectively. In the case of Fig. 1(c), annual emissions for all scenarios increased in the first part of the 21st century, followed by a steep decline of emissions to the level of persistent natural carbon sinks. The peak allowable emissions, as well as the rate of emissions decline varied as a function of the CO_2 stabilization level, with higher stabilization levels allowing for higher and more sustained levels of anthropogenic CO_2 emissions. Furthermore, the timing of the peak emissions level varied by about 35 yr between scenarios, from a peak value of 9.7 GtC/yr (where 1 GtC/yr $=10^{15}$ grams of carbon per year) occurring at 2015 in the case of the OSP350 scenario, to a peak value of 12 GtC/yr occurring at 2050 in the case of SP1000.

The timing and value of the peak emissions level was also sensitive to the trajectory taken to stabilization; comparing SP550 with DSP550, for example, shows that the delayed CO_2 turning point in the DSP550 scenario allowed for an increase in the peak annual emissions from 10.7 GtC/yr in the case of SP550, to 12 GtC/yr for DSP550. This increased peak emissions value was also associated with an 15 yr offset of the timing of peak emissions from 2027 (SP550) to 2042 (DSP550). Similarly, peak emissions for the 450 scenarios ranged from 10 GtC/yr at 2018 for SP450, to 11.4 GtC/yr at 2030 for DSP450, to 11.5 GtC/yr in 2033 for OSP450. However, as is shown in Fig. 1(d), cumulative emissions beyond about 2150 did not depend on the trajectory taken to stabilization. Despite notable differences in emissions over the next century, all three 450 (and both 550) scenarios resulted in equivalent long-term CO_2 emissions. The conclusion here is that for the range of scenarios explored here, both stabilization level and multicentury global warming were sensitive only to the total anthropogenic emission of CO_2, and not to the trajectory of emissions taken over the next century.

Finally, in the case of both overshoot scenarios (OSP350 and OSP450), extended periods of negative emissions were required to achieve the stabilization targets. This result speaks to the importance of CO_2 capture and storage as a critical component of any policy aimed at CO_2 stabilization at levels close to or lower than present-day atmospheric CO_2 levels. In the case of the OSP350 scenario, at least 300 GtC must be removed from the atmosphere between 2080 and 2240 in order to reduce atmospheric CO_2 to 350 ppmv by the year 2200. This value is a minimum estimate, given that there would also likely be positive carbon emissions over this time period. It is noteworthy that this requirement for CO_2 capture and storage exceeds estimates of the total historical emissions of fossil fuel carbon to date (Marland et al., 2002).

3.2. Stabilization at 550 ppmv

As shown in Fig. 1(b), the SP550 scenario run was characterized by a total global warming of 3.4 °C between 1800 and 2400, 2.6 °C of which occurred after the year 2000. Warming over the 21st century was 1.6 °C. Precipitation also increased in the model by close to 2.5 % relative to pre-industrial levels by 2400, though this global increase was dominated by increases over oceans, with land precipitation actually decreasing slightly over the next 400 yr. In general, soil moisture over land increased as a result of increased soil water use efficiency by terrestrial vegetation in response to increased CO_2, with a corresponding increase in terrestrial runoff. Global surface ocean temperature increased by 2.7 °C at 2400 relative to pre-industrial, with continued warming over the following several centuries. Meridional overturning reached a minimum value of 17.2 Sv ($=10^6$ m^3/s) at 2100, but had largely recovered to the present-day value of about 20 Sv by the year 2400.

Pre-industrial carbon storage in the model totalled 31 000 GtC in the ocean and 1600 GtC on land (610 in vegetation, 990 in soil). In response to increased atmospheric CO_2 and climate changes, total ocean and land carbon stores increased by 660 and 325 GtC, respectively, between 1800 and 2400. While ocean carbon continued to increase beyond the year 2400, land carbon uptake saturated in the model around the year 2100, with a small continuing vegetation carbon sink offsetting a soil carbon source. Soil carbon residence time decreased from 16.3 yr in 1800 to just under 12.7 yr in 2400; in contrast, global vegetation carbon residence time did not decrease notably, but rather remained close to 10 yr throughout the model run. The model also simulated changes in vegetation distributions; in general, both leaf area index and spatial distributions of forest plant types in the model (broadleaf and needleleaf trees) expanded in response to increased CO_2 and climate warming—in most cases, this occurred at the expense of other vegetation types in the model (C_3/C_4 grasses and shrubs). The strongest signal of vegetation distribution changes occurred at high northern latitudes, with boreal forests expanding and migrating northward on the order of 5 degrees latitude due to more favourable growing conditions. There was also a decrease in forest cover and an associated increase in the extent of both C_3 and C_4 grass distributions at the southerly extent of the boreal forest range.

The above description applies to the standard model configuration as forced by the SP550 scenario, listed in Table 1 as run CS4.2. The other seven runs listed in Table 1 differed considerably in their response to the SP550 forcing, as a result of differences in both climate sensitivity, and the strength of carbon cycle feedbacks. These differences are illustrated in Fig. 2, which shows the modelled global surface air temperature for each of the eight SP550 model runs. Runs CS2.6 and CS5.4 simulated warming between 1800 and 2400 of 1.8 °C and 4.5 °C, respectively, as a result of their respective decreased and increased climate sensitivities. Run CS0 also showed a small warming (0.4 °C between 1800 and 2400), despite in this case an absence of direct CO_2 radiative forcing. However, CO_2 increases in this run did affect the growth and distribution of terrestrial vegetation, and consequently affected changes to the land surface via dynamic vegetation changes. These changes were of sufficient magnitude to result in the small global warming seen in this simulation. The CS0NF run, in contrast, did not include either direct CO_2 radiative forcing or CO_2 fertilization, and consequently did not simulate any warming beyond the year 2000. Similarly, each of the other three non-CO_2 fertilized runs (CS2.6NF, CS4.2NF and CS5.4NF) simulated a global warming of about a quarter to a third of a degree less than their CO_2-fertilized counterparts due to the absence of CO_2-induced dynamic vegetation feedbacks.

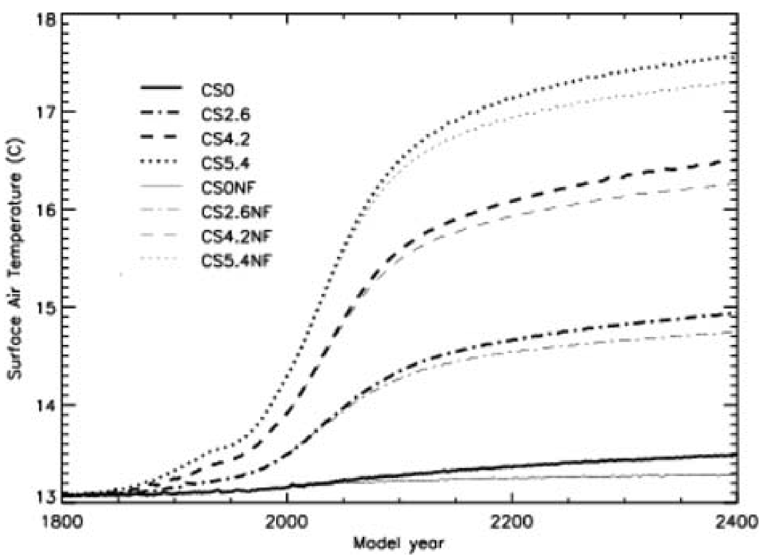

Fig. 2. Modelled global surface air temperature for the eight runs listed in Table 1 forced by the SP550 scenario. Differences in temperature change between CS0, CS2.6, CS4.2 and CS5.4 reflect different climate sensitivities. Differences between NF runs and their corresponding CS runs reflect the effect of removing CO_2 fertilization (and consequent dynamic vegetation feedbacks) after 2000.

Changes in vegetation and ocean carbon stores occurred in all model runs in response to both climate changes and increases in atmospheric CO_2, with (at a global scale) increased CO_2 driving increased sequestration of carbon in terrestrial and oceanic carbon sinks, and climate changes contributing to reduced carbon uptake. As described previously, it is these global changes in carbon stocks that determined the overall fate of anthropogenic CO_2 in the model, and consequently affected the anthropogenic CO_2 emissions consistent with atmospheric CO_2 stabilization at 550 ppmv.

3.2.1. Effect of positive carbon cycle-climate feedbacks. The effect of positive carbon cycle-climate feedbacks on emissions targets for stabilization can be isolated by performing a simulation in which climate is held constant at pre-industrial conditions; as a result, carbon sinks in the model are affected only by increased atmospheric CO_2. The emissions that resulted from this simulation (CS0) are shown in Fig. 3(a), as the solid black line. Due to the absence of negative climate impacts on carbon uptake, both terrestrial and oceanic carbon sinks were stronger throughout the model simulation. Consequently, anthropogenic emissions in this run were higher relative to the standard climate change simulation [CS4.2, shown in Fig. 3(a) as the dashed line, as well as in Fig. 1]. Also shown in Fig. 3(a) are two additional simulations whose climate sensitivities were varied as described in Section 2.2. Decreasing climate sensitivity from 4.2 °C to 2.6 °C [run CS2.6; dot-dashed line in Fig. 3(a)], resulted in intermediate emissions levels between runs CS0 and CS4.2. Increasing climate sensitivity to 5.4 °C resulted in smaller emissions as a result of increased climate changes and associated increased negative impact on global carbon sinks.

Emissions differences between each coupled run (CS2.6, CS4.2, CS5.4) and the uncoupled-climate simulation (CS0) are shown in Fig. 3(b). This plot shows explicitly the effect of climate changes on annual emissions targets for 550-stabilization as a function of time throughout the model simulations. The peak emissions reduction occurred around at the midpoint of the 21st century in all three model versions, with maximum emissions reductions of −1.06 (CS2.6), −2.33 (CS4.2) and −3.25 (CS5.4) GtC/yr relative to CS0. At 2050, this represented an allowable emissions reduction due to positive carbon cycle-climate feedbacks of 9%, 20% and 28% relative to year 2050 CS0 emissions for runs CS2.6, CS4.2 and CS5.4, respectively.

Cumulative emissions reductions from the year 2005 until 2400 are shown in Fig. 3(c) for each model run relative to its difference from CS0 at the year 2005. This panel shows the cumulative effect of increasing climate sensitivity on the strength of carbon cycle-climate feedbacks and hence on emissions targets. Cumulative emissions were reduced by 40, 91 and 130 GtC by 2050, for runs CS2.6, CS4.2 and CS5.4, respectively. At 2100, cumulative emissions reductions totalled 87 (CS2.6), 190 (CS4.2) and 264 (CS5.4) GtC; at 2400: 191 (CS2.6), 392 (CS4.2) and 538 (CS5.4) GtC. Considering that total emissions between 2005 and 2400 for the CS0 run equalled 1482 GtC,

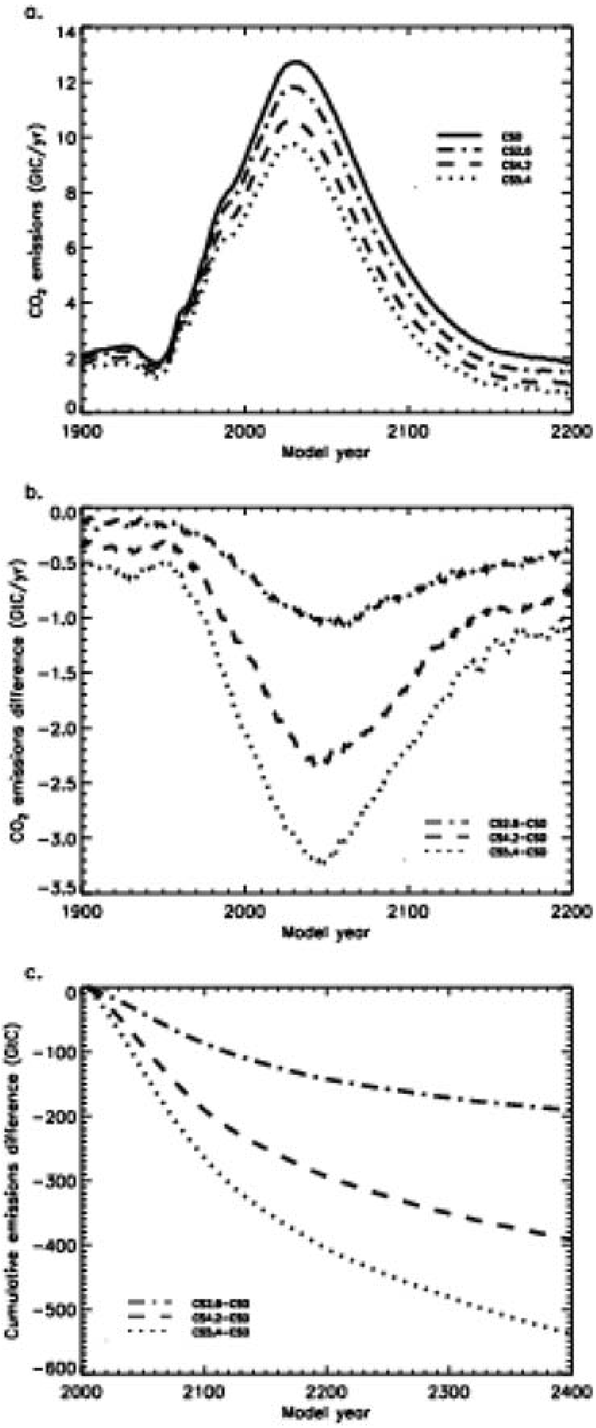

Fig. 3. Effect of positive carbon cycle-climate feedbacks on emissions targets for stabilization at 550 ppmv. (a) Annual anthropogenic CO_2 emissions for the uncoupled-climate run (CS0: solid line), and three coupled runs with climate sensitivities of 2.6 °C (CS2.6: dot-dashed line), 4.2 °C (CS4.2: dashed line) and 5.4 °C (CS5.4: dotted line). (b) Annual emissions difference between coupled runs (CS2.6, CS4.2 and CS5.4) and the uncoupled-climate run (CS0). (c) As (b), but for the cumulative emissions difference.

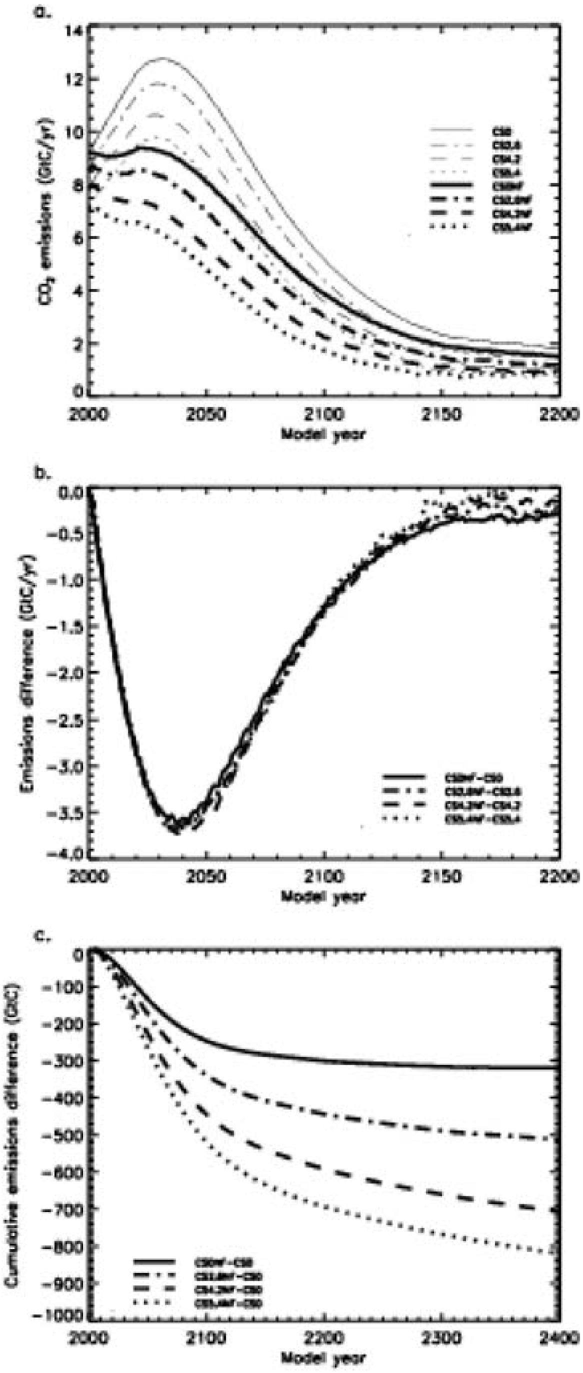

Fig. 4. Effect of negative CO_2 fertilization feedbacks on emissions targets for stabilization at 550 ppmv. (a) Annual anthropogenic CO_2 emissions: thin lines show the runs with CO_2 fertilization active, as plotted in Figure 2(a); thick lines represent equivalent runs without future CO_2 fertilization of the terrestrial carbon sink. (b) Annual emissions difference between runs no-CO_2 fertilization runs and the equivalent CO_2 fertilized simulation. (c) Cumulative emissions reductions due to the combination of both positive carbon cycle-climate feedbacks, and the absence of CO_2 fertilization, plotted here as the difference between no-CO_2 fertilization runs and the uncoupled-climate simulation.

the cumulative effect of positive carbon cycle-climate feedbacks was to substantially reduce total allowable emissions; in the extreme case (CS5.4) cumulative emissions were reduced to less than two thirds the allowable emissions in the absence of these feedbacks.

3.2.2. Effect of negative CO_2 fertilization feedbacks. CO_2 fertilization of vegetation growth represents the predominant driver of terrestrial carbon uptake in this (and most other) climate-carbon models (Friedlingstein et al., 2006). As such, removing this effect would be expected to result in a dramatically reduced terrestrial carbon sink, and consequently in a reduction of the emissions required to achieve CO_2 stabilization. This is shown in Fig. 4(a), where the four runs described in the previous Section (3.2.1) are plotted (thin lines) along with the four additional runs in which CO_2 fertilization was held constant at present-day levels (thick lines). In all cases, removing CO_2 fertilization as a viable mechanism for an increased future terrestrial carbon sink led to large decreases in allowable emissions over the next several centuries.

Differences between non- and CO_2-fertilized runs for each value of climate sensitivity are plotted in Fig. 4(b). Maximum emissions reductions due to the removal of CO_2 fertilization occurred around the year 2040, with all model configurations showing peak reductions of around 3.7 GtC/yr. Interestingly, the effect of removing CO_2 fertilization shown here is independent of climate sensitivity, as each model configuration showed a very similar pattern of annual emissions reductions. Furthermore, the effect of positive carbon cycle-climate feedbacks (as influenced by varying climate sensitivity) was not greatly influenced by the presence or absence of CO_2 fertilization (e.g. CS4.2-CS0 compared to CS4.2NF−CS0NF—these differences are not plotted explicitly). This result appears contradictory to previous studies which have shown an increased strength of carbon cycle-climate feedbacks due to reduced CO_2 fertilization (Thompson et al., 2004; Friedlingstein et al., 2006). However, these studies were all carried out using climate-carbon models forced by emissions scenarios, and as such the time-evolution of atmospheric CO_2 (and hence of climate changes) in the models were influenced strongly by both positive and negative carbon cycle feedbacks. In the present study, atmospheric CO_2 was prescribed, and hence the climate changes in the model were not themselves responsive to carbon cycle feedbacks. What this means is that in a model simulation forced by prescribed CO_2, opposing carbon cycle feedbacks operate independently.

Figure 4(c) shows the cumulative effect on calculated emissions of both the presence of positive carbon cycle-climate feedbacks and the absence of CO_2 fertilization. The solid black line (CS0NF−CS0) represents the effect of removing CO_2 fertilization on its own, in the absence of carbon cycle-climate feedbacks. This shows that the absence of future CO_2 fertilization led to a decrease in cumulative emissions of 133 Gt by 2050, 247 GtC by 2100 and 320 GtC at 2400. As can also be seen here, the effect of CO_2 fertilization is concentrated over the next century. The importance of the CO_2 fertilization feedback reflects the trajectory of atmospheric CO_2 increases; once CO_2 is stabilized in the atmosphere (after 2150 in this scenario), this feedback becomes of negligible importance in determining emissions targets.

The dot-dashed, dashed and dotted lines in Fig. 4(c) represent the effect of removing CO_2 fertilization in conjunction with the effect of positive carbon cycle-climate feedbacks associated with climate sensitivities of 2.6 °, 4.2 ° and 5.4 °C, respectively. In the case of CS2.6NF, cumulative emissions were reduced by 174, 339 and 512 GtC by 2050, 2100 and 2400, respectively. Corresponding reductions for CS4.2NF equalled 227, 445 and 707 GtC; for CS5.4NF: 264, 518 and 820 GtC. In the extreme case (no CO_2 fertilization and high climate sensitivity), total emission reductions due to carbon cycle feedbacks exceeded 55% of total CS0 emissions from 2005 to 2400.

4. Discussion

The recent application of coupled climate-carbon models to the projection of future atmospheric CO_2 increases has demonstrated the potential for strong carbon cycle feedbacks over the coming century (Cox et al., 2000; Dufresne et al., 2002; Jones et al., 2003; Thompson et al., 2004; Zeng et al., 2004; Govindasamy et al., 2005; Fung et al., 2005; Matthews et al., 2005b,a). Positive terrestrial carbon cycle-climate feedbacks result from a combination of increased soil respiration and decreased vegetation productivity due to climate changes; in the oceanic carbon cycle, positive feedbacks result from decreased CO_2 solubility with increasing ocean temperature, as well as changes in ocean buffering capacity, ocean circulation and the solubility pump (Friedlingstein et al., 2003, 2006).

The net effect of these carbon cycle-climate feedbacks is to amplify the growth of atmospheric CO_2 over the 21st century (Friedlingstein et al., 2006). In general, however, the net carbon cycle feedback in these models is negative, whereby negative feedbacks (e.g. CO_2 fertilization in the terrestrial carbon cycle) exceed the effect of positive carbon cycle-climate feedbacks (e.g. Thompson et al., 2004; Matthews et al., 2005b). The exceptions to this are in the case of the HadCM3LC (Cox et al., 2000; Jones et al., 2003) and UMD (Zeng et al., 2004) models, which both simulated a terrestrial sink-to-source transition during the 21st century. This transition occurs when the magnitude of positive terrestrial carbon cycle-climate feedbacks exceed that of negative CO_2 fertilization feedbacks. On the oceanic side, the direct effect of elevated CO_2 on ocean carbon uptake outweighed the effects of positive carbon cycle-climate feedbacks, resulting in a net negative ocean carbon cycle feedback in all of the above model studies (Friedlingstein et al., 2006).

In this paper, I have shown that these same carbon cycle feedbacks can have dramatic implications for emissions targets that are set with the aim of stabilizing atmospheric CO_2. The actual amount by which emissions were affected by carbon cycle feedbacks in these simulations is model-specific, given the large range in simulated feedbacks among coupled climate-carbon cycle models. Known uncertainties in the magnitude of carbon cycle feedbacks, such as the uncertainties associated with soil carbon (Jones et al., 2005), vegetation productivity (Matthews et al., 2005a) and ocean circulation and carbon cycle (Friedlingstein et al., 2003) responses to climate change, would contribute directly to uncertainties in emissions targets. Uncertainties in the potential future variability of these processes has not been considered in this study, and further sensitivity studies would be very useful in assessing how different model representations of carbon cycle processes may affect emissions targets (see Jones et al., 2006b, this issue).

A recent intercomparison of simulations from ten coupled climate-carbon models highlighted the very large range of future positive carbon cycle-climate feedbacks between models (Friedlingstein et al., 2006). Models with larger feedbacks — for example, HadCM3LC (Cox et al., 2000) — would produce larger emissions reductions than those described here; correspondingly, models with smaller feedbacks — for example, NCAR/CSM1 (Fung et al., 2005) — would predict smaller emissions reductions. A challenge in future climate-carbon research will be to narrow this range of model results, so as to reduce this large uncertainty in future climate projections. It is worth noting, however, that in this intercomparison, the UVic ESCM was found to fall close to the midpoint of the range of model results, both with respect to the magnitude of carbon cycle-climate feedbacks and also the strength of CO_2 fertilization (Friedlingstein et al., 2006). As such, the effect of these feedbacks on CO_2-stabilizing emissions in the UVic Model would also be close to the midpoint of that simulated by other models.

It is worth noting also that the results presented here would also be modified to some extent by processes not currently included in the UVic ESCM. Specifically, this version of the UVic ESCM does not include changes in ocean biology or the process of carbonate compensation in the ocean, both of which could likely affect the uptake of anthropogenic carbon in the ocean over the next several centuries (Joos et al., 1999; Archer et al., 2004; Sarmiento et al., 2004). Additionally, spatial changes in land use, dynamic nitrogen cycling and anthropogenic nitrogen deposition were not included in these simulations, all of which have the potential to affect future terrestrial carbon uptake (Hungate et al., 2003; Lamarque et al., 2005; Sitch et al., 2005). I would argue, however, that the uncertainties that are addressed in this study (i.e. the effect of climate sensitivity on carbon cycle-climate feedbacks, and the contribution of CO_2 fertilization to the terrestrial carbon sink) are first-order effects with respect to determining the carbon cycle response to future environmental change.

Numerous recent studies have constructed estimates of climate sensitivity, and all of them have presented a very large range of possible climate sensitivities (e.g. Frame et al., 2005; Forest et al., 2006). In particular, it has not been possible to determine an upper limit for climate sensitivity, and values greater than 10 °C for a doubling of atmospheric CO_2 have been presented as unlikely yet possible (Stainforth et al., 2005). The implication of this large uncertainty for the carbon cycle is profound: several modelling studies have demonstrated that the strength of carbon cycle-climate feedbacks depends strongly on the model's climate sensitivity (Govindasamy et al., 2005; Matthews et al., 2005a,b), and it is likely that a significant portion of the variability in feedback strength between models can be traced to models' differing climate sensitivities (Friedlingstein et al., 2003, 2006). In this study, I have shown that this uncertainty in climate sensitivity has definite implications for emissions targets aimed at CO_2 stabilization. Increasing climate sensitivity in the model from 2.6 to 5.4 °C, for example, led to reductions in total allowable emissions of almost 350 GtC between 2005 and 2400, as a result of larger positive carbon cycle feedbacks to climate.

It is worth emphasizing here that while a climate sensitivity range of 2.6 to 5.4 °C is on the high side of estimates of the likely range of climate sensitivity (e.g. 1.5–4.5 °C: Houghton et al., 2001), it is well within the range of possible climate sensitivities (e.g. Forest et al., 2006; Hegerl et al., 2006). However, given the range of probabilities associated with different estimates of climate sensitivities, runs CS2.6 and CS4.6 are more representative of the 'most likely' ranges of climate sensitivity in most available estimates. Furthermore, these runs also simulate historical temperature changes and anthropogenic CO_2 emissions closest to those observed, giving these runs somewhat more credibility than runs CS0 or CS5.4. I caution, however, that historical temperature changes are not a good constraint to impose on these runs, given that important historical climate forcings, such as non-CO_2 greenhouse gases and sulphate aerosols, were not included in these simulations.

The uncertainty associated with the role of CO_2 fertilization in the terrestrial carbon cycle remains large, despite a considerable body of research on this topic over the last several years (see reviews by Schimel et al., 2001; Adams and Piovesan, 2002; Karnosky, 2003; Nowak et al., 2004). While it is clear that plants have the potential to increase production in response to elevated CO_2, field experiments have been far from unanimous in either supporting or negating the ability of increased CO_2 to stimulate vegetation growth in real ecosystems (Oren et al., 2001; DeLucia et al., 2005; Norby et al., 2005). By comparing simulations with and without future CO_2 fertilization, the results in this study represent upper and lower bounds on the uncertainty associated with CO_2 fertilization with respect to emissions targets for CO_2 stabilization. This uncertainty is very large: for example, in the absence of CO_2 fertilization, allowable emissions were reduced by close to 250 GtC over the next century alone. It is clear that obtaining stronger evidence for or against CO_2 fertilization is of critical importance so as to better constrain future projections of emissions that are required to achieve a desired CO_2 stabilization target.

5. Conclusions

The results described in this paper represent a new quantification of the effects of carbon cycle feedbacks on emission targets for CO_2 stabilization. The specific quantities presented here are model-specific and subject to the numerous uncertainties outlined above with respect to the carbon cycle response to environmental change. However, it is clear that climate sensitivity uncertainty is of critical importance — both with respect to its direct relevance for ascertaining future global warming, and also (as demonstrated here) due to its compounding influence on the magnitude of positive carbon cycle-climate feedbacks. Additionally, the future magnitude of the CO_2-fertilized terrestrial carbon sink has profound implications for the carbon cycle's ability to absorb future anthropogenic emissions of CO_2.

Carbon cycle feedbacks over the next years to centuries will determine how quickly CO_2 accumulates in the atmosphere, and as such will be of primary importance in determining how much carbon is 'safe' to emit if we are to 'prevent dangerous anthropogenic influence with the climate system (United Nations, 1992)'. The emissions reductions necessary to accommodate the feedbacks shown here are very large, and from this it is clear that future carbon cycle changes cannot be ignored in decision making aimed at stabilizing atmospheric CO_2 levels.

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References

Adams, B., White, A. and Lenton, T. M. 2004. An analysis of some diverse approaches to modelling terrestrial net primary productivity. *Ecol. Model.* **177**, 353–391.

Adams, J. M. and Piovesan, G. 2002. Uncertainties in the role of land vegetation in the carbon cycle. *Chemosphere* **49**, 805–819.

Archer, D., Martin, P., Buffett, B., Brovkin, V., Rahmstorf, S. and co-authors. 2004. The importance of ocean temperature to global biogeochemistry. *Earth Planet. Sc. Lett*. **222**, 333–348.

Caspersen, J. P., Pacala, S. W., Jenkins, J. C., Hurtt, G. C., Moorcroft, P. R. and co-authors. 2000. Contributions of land-use history to carbon accumulation in US forests. *Science* **290**, 1148–1151.

Cox, P. M. 2001. *Description of the 'TRIFFID' Dynamic Global Vegetation Model*, Hadley Center Technical Note 24, Met Office, UK.

Cox, P. M., Betts, R. A., Bunton, C. B., Essery, R. L. H., Rowntree, P. R. and co-authors. 1999. The impact of new land surface physics on the GCM simulation of climate and climate sensitivity. *Clim. Dynam.* **15**, 183–203.

Cox, P. M., Betts, R. A., Jones, C. D., Spall, S. A. and Totterdell, I. J. 2000. Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. *Nature* **408**, 184–187.

DeLucia, E. H., Moore, D. J. and Norby, R. J. 2005. Contrasting responses of forest ecosystems to rising atmospheric CO_2: Implications for the global C cycle. *Global Biogeochem. Cy.* **19**, GB3006.

Dufresne, J.-L., Friedlingstein, P., Berthelot, M., Bopp, L., Ciais, P. and co-authors. 2002. On the magnitude of positive feedback between future climate change and the carbon cycle. *Geophys. Res. Lett.* **29**, 1405.

Enting, I. G., Wigley, T. M. L. and Heimann, M. 1994 *Future Emissions and Concentrations of Carbon Dioxide: Key Ocean/Atmosphere/Land analysis*, CSIRO Division of Atmospheric Research Technical Paper No. 31.

Essery, R. L. H., Best, M. J., Betts, R. A., Cox, P. M. and Taylor, C. M. 2003. Explicit representation of subgrid heterogeneity in a GCM land surface scheme. *J. Hydrometeorol.* **4**, 530–543.

Ewen, T. L., Weaver, A. J. and Eby, M. 2004. Sensitivity of the inorganic ocean carbon cycle to future climate warming in the UVic coupled model. *Atmos. Ocean* **42**, 23–42.

Forest, C. E., Stone, P. H. and Sokolov, A. P. 2006. Estimated PDFs of climate system properties including natural and anthropogenic forcings. *Geophys. Res. Lett.* **33**, L01, 705.

Frame, D. J., Booth, B. B. B., Kettleborough, J. A., Stainforth, D. A., Gregory, J. M. and co-authors. 2005. Constraining climate forecasts: The role of prior assumptions. *Geophys. Res. Lett.* **32**, L09, 702.

Friedlingstein, P., Bopp, L., Ciais, P., Dufresne, J.-L., Fairhead, L. and co-authors. 2001. Positive feedback between future climate change and the carbon cycle. *Geophys. Res. Lett.* **28**, 1543–1546.

Friedlingstein, P., Dufresne, J.-L., Cox, P. M. and Rayner, P. 2003. How positive is the feedback between future climate change and the carbon cycle?, *Tellus*. **55B**, 692–700.

Friedlingstein, P., Cox, P., Betts, R., von Bloh, W., Brovkin, V. and co-authors. 2006. Climate-carbon cycle feedback analysis, results from the C^4MIP model intercomparison. *J. Clim.*, **19**, 3337–3353.

Fung, I. Y., Doney, S. C., Lindsay, K. and John, J. 2005. Evolution of carbon sinks in a changing climate. *P. Natl. Acad. Sci. USA.* **102**, 11, 201–11, 206.

Govindasamy, B., Thompson, S., Mirin, A., Wickett, M., Caldeira, K. and co-authors. 2005. Increase of carbon cycle feedback with climate sensitivity: results from a coupled climate and carbon cycle model. *Tellus* **57B**, 153–163.

Hegerl, G. C., Crowley, T. J., Hyde, W. T. and Frame, D. J. 2006. Constraints on climate sensitivity from temperature reconstructions of the last millenium. *Nature* **440**, 1029–1032.

Houghton, J. T., Meira Filho, L. G., Callander, B. A., Harris, N., Kattenberg, A. and co-authors. (Eds.). 1995. *Climate Change 1994: Radiative Forcing of Climate Change and an Evaluation of the IPCC IS92 Emission Scenarios*, 339 pp., Camb. Univ. Press, UK.

Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., P. J. van der Linden and co-authors (Eds.). 2001. *Climate Change 2001: The Scientific Basis*, 944 pp., Camb. Univ. Press, UK.

Hungate, B. A., Dukes, J. S., Shaw, M. R., Luo, Y. and Field, C. B. 2003. Nitrogen and climate change. *Science* **302**, 1512–1513.

Jones, C., McConnell, C., Coleman, K., Cox, P., Falloon, P. and co-authors. 2005. Global climate change and soil carbon stocks; predictions from two contrasting models for the turnover of organic carbon in soil. *Glob. Change Biol.* **11**, 154–166.

Jones, C. D., Cox, P. M., Essery, R. L. H., Roberts, D. L. and Woodage, M. J. 2003. Strong carbon cycle feedbacks in a climate model with interactive CO_2 and sulphate aerosols. *Geophys. Res. Lett.* **30**, 1479.

Jones, C. D., Cox, P. M. and Huntingford, C. 2006a. Impact of climate-carbon cycle feedbacks on emissions scenarios to achieve stabilisation. in *Avoiding Dangerous Climate Change* (eds H. J. Schellnhuber, W. Cramer, N. Nakicenovic, T. Wigley and G. Tohe) pp. 323–331, Camb. Univ. Press, UK.

Jones, C. D., Cox, P. M. and Huntingford, C. 2006b. Climate-carbon cycle feedbacks under stabilisation: uncertainty and observational constraints. *Tellus*, this issue.

Joos, F., Plattner, G.-K., Stocker, T. F., Marchal, O. and Schmittner, A. 1999. Global warming and marine carbon cycle feedbacks on future atmospheric CO_2. *Science* **284**, 464–467.

Joos, F., Prentice, I. C., Sitch, S., Meyer, R., Hooss, G. and co-authors. 2001. Global warming feedbacks on terrestrial carbon uptake under the Intergovernmental Panel on Climate Change (IPCC) emissions scenarios. *Global Biogeochem. Cy.* **15**, 891–907.

Joos, F., Prentice, I. C. and House, J. I. 2002. Growth enhancement due to global atmospheric change as predicted by terrestrial ecosystem models: consistent with us forest inventory data. *Glob. Change Biol.* **8**, 299–303.

Karnosky, D. F. 2003. Impacts of elevated atmospheric CO_2 on forest trees and forest ecosystems: knowledge gaps. *Environ. Int.* **29**, 161–169.

Kheshgi, H. S. and Jain, A. K. 2003. Projecting future climate change: implications of carbon cycle model intercomparisons. *Glob. Change Biol.* **17**, 1047.

Knutti, R., Joos, F., Müller, S. A., Plattner, G.-K. and Stocker, T. F. 2005. Probabilistic climate change projections for CO_2 stabilization profiles. *Geophys. Res. Lett.* **32**, L20, 707.

Lamarque, J.-F., Kiehl, J. T., Brasseur, G. P., Butler, T., Cameron-Smith, P. and co-authors. 2005. Assessing future nitrogen deposition and carbon cycle feedback using a multimodel approach: analysis of nitrogen deposition. *J. Geophys. Res.* **110**, D19, 303.

Marland, G., Boden, T. A. and Andres, R. J. 2002. Global, regional, and national annual CO_2 emissions from fossil-fuel burning, cement production, and gas flaring: 1751-2000. in *CDIAC NDP-030*, p. http://cdiac.esd.ornl.gov/trends/trends.htm, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, TN.

Matthews, H. D. 2005. Decrease of emissions required to stabilize atmospheric CO_2 due to positive carbon cycle-climate feedbacks. *Geophys. Res. Lett.* **32**, L21, 707.

Matthews, H. D., Eby, M., Weaver, A. J. and Hawkins, B. J. 2005a. Primary productivity control of simulated carbon cycle-climate feedbacks. *Geophys. Res. Lett.* **32**, L14, 708.

Matthews, H. D., Weaver, A. J. and Meissner, K. J. 2005b. Terrestrial carbon cycle dynamics under recent and future climate change. *J. Clim.* **18**, 1609–1628.

Meissner, K. J., Weaver, A. J., Matthews, H. D. and Cox, P. M. 2003. The role of land-surface dynamics in glacial inception: a study with the UVic Earth System Climate Model. *Clim. Dynam.* **21**, 515–537.

Norby, R. J., DeLucia, E. H., Gielen, B., Calfapietna, C., Grardina, C. P. and co-authors. 2005. Forest response to elevated CO_2 is conserved across a broad range of productivity. *P. Natl. Acad. Sci. USA.* **102**, 18052, 18056.

Nowak, R. S., Ellsworth, D. S., Smith, S. D. 2004. Functional responses of plants to elevated atmospheric CO_2 - do photosynthetic and productivity data from FACE experiments support early predictions? *New phytol.*, **162**, 253, 280.

O'Neill, B. C. and Oppenheimer, M. 2004. Climate change impacts are sensitive to the concentration stabilization path. *P. Natl. Acad. Sci. USA.* **101**, 16,411–16,414.

Oren, R., Ellsmorth, D. S., Johnsen, K., Phillips, N., Ewers, B. E. and co-authors. 2001. Soil fertility limits carbon sequestration by forest ecosystems in a CO_2-enriched atmosphere. *Nature* **411**, 469–472.

Orr, J., Najjar, C. R., Sabine, C. L. and Joos, F. 1999 *Abiotic-HOWTO*,. Internal OCMIP Report, 25 pp., LCSE/CEA Saclay, Gif-sur-Yvette, France.

Prentice, C., Farquhar, G. D., Fasham, M. J. R., Goulden, M. L., Heimann, M. and co-authors. 2001. The carbon cycle and atmospheric carbon dioxide. in *Climate Change 2001: The Scientific Basis*, edited by J. Houghton *et al*., pp. 183–237, Camb. Univ. Press, UK.

Sabine, C. L., Feely, R. A., Gruber, N., Key, R. M., Lee, K., and co-authors. 2004. The oceanic sink for anthropogenic CO_2. *Science* **305**, 367–371.

Sarmiento, J. L., Slater, R., Barber, R., Bopp, L., Doney, S. C. and co-authors. 2004. Response of ocean ecosystems to climate warming. *Glob. Change Biol.* **18**, GB3003.

Schimel, D., Grubb, M., Joos, F., Kaufmann, R., Moss, R. and co-authors. 1997. *Stabilization of Atmospheric Greenhouse Gases: Physical*, *Biological and Socio-economic Implications – IPCC Technical Paper III*, 52 pp., Intergovernmental Panel on Climate Change, Geneva, Switzerland.

Schimel, D. S., House, J. I., Hibbard, K. A., Bousquet, P., Clais, P. and co-authors. 2001. Recent patterns and mechanisms of carbon exchange by terrestrial ecosystems. *Nature* **414**, 169–172.

Sitch, S., Brovkin, V., von Bloh, W., van Vuuren, D., Eickhout, B. and Ganopolski, A. 2005. Impacts of future land cover changes on atmospheric CO_2 and climate. *Global Biogeochem. Cy.* **19**, GB2013.

Stainforth, D. A., Alna, T., Christensen, C., Collins M., Faull, N. and co-authors. 2005. Uncertainty in predictions of the climate response to rising levels of greenhouse gases. *Nature* **433**, 403–406.

Stocker, T. F. and Schmittner, A. 1997. Influence of CO_2 emission rates on the stability of the thermohaline circulation. *Nature* **1388**, 862–865.

Thompson, S. L., Govindasamy, B., Mirin, A., Caldeira, K., Delire, C. and co-authors. 2004. Quantifying the effects of CO_2-fertilized vegetation on future global climate and carbon dynamics. *Geophys. Res. Lett.* **31**, L23, 211.

United Nations. 1992 *Earth Summit Convention on Climate Change*,, United Nations Conference on Environment and Development, Rio de Janeiro, Brazil.

Vetter, M., Wirth, C., Böttcher, H., Churkina, G., Schulze, E.-D., Wutzler, T. and co-authors.. 2005. Partitioning direct and indirect human-induced effects on carbon sequestration of managed coniferous forests using model simulations and forest inventories. *Glob. Change Biol.* **11**, 1–18.

Weaver, A. J., Eloy, M., Wiebe, E. C., Bitz, C. M., Duffy, P. B. and co-authors. 2001. The UVic Earth System Climate Model: Model description, climatology and applications to past, present and future climates. *Atmos. Ocean* **39**, 361–428.

Wigley, T. M. L., Richels, R. and Edmonds, J. A. 1996. Economic and environmental choices in the stabilization of atmospheric CO_2 concentrations. *Nature* **379**, 240–243.

Zeng, N., Qian, H. and Munoz, E. 2004. How strong is carbon cycle-climate feedback under global warming?, *Geophys. Res. Lett.*. **31**, L20, 203.