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Carbon-cycle feedbacks increase the likelihood of a warmer future

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[1] Positive carbon-cycle feedbacks have the potential to reduce natural carbon uptake and accelerate future climate change. In this paper, we introduce a novel approach to incorporating carbon-cycle feedbacks into probabilistic assessments of future warming. Using a coupled climate-carbon model, we show that including carbon-cycle feedbacks leads to large increases in extreme warming probabilities. For example, for a scenario of CO_2 stabilization at 550 ppm, the probability of exceeding 2°C warming at 2100 increased by a factor of between 1.7 and 3, while the probability of exceeding 3°C warming increased from a few percent to as much as 22%. CO_2 fertilization was found to exert little influence on the amount of future warming, since increased carbon uptake was partially offset by fertilization-induced surface albedo changes. The effect of positive carbon-cycle feedbacks on the likelihood of extreme future warming must be incorporated into climate policy-related decision making. **Citation:** Matthews, H. D., and D. W. Keith (2007), Carbon-cycle feedbacks increase the likelihood of a warmer future, *Geophys. Res. Lett.*, *34*, L09702, doi:10.1029/2006GL028685.

1. Introduction

[2] Predicting the magnitude of future climate warming is subject to large uncertainty. There is uncertainty in future carbon emissions, given incomplete knowledge of future economic directions [*Nakićenović et al.*, 2000]. For a given future CO_2 emissions scenario, uncertainty in global carbon sinks leads to uncertainty in the rate of CO_2 accumulation in the atmosphere [*Prentice et al.*, 2001]. For a given atmospheric CO_2 increase, the climate warming response (climate sensitivity) is also very uncertain [*Frame et al.*, 2005; *Piani et al.*, 2005; *Forest et al.*, 2006; *Hegerl et al.*, 2006; *Knutti et al.*, 2006]. Climate changes will likely weaken carbon sinks, leading to positive carbon-cycle feedbacks (of uncertain strength) that would accelerate the rate of CO_2 accumulation in the atmosphere and increase future climate changes [*Friedlingstein et al.*, 2006]. Probabilistic assessments of future climate change aim to incorporate each of these levels of uncertainty so as to estimate the likelihood of future warming [e.g., *Wigley and Raper*, 2001].

[3] Numerous recent studies using coupled climate-carbon models have demonstrated the potential for positive feedbacks between climate change and the carbon-cycle to accelerate the rise of atmospheric CO_2 over the next century [*Cox et al.*, 2000; *Joos et al.*, 2001; *Dufresne et al.*, 2002; *Zeng et al.*, 2004; *Govindasamy et al.*, 2005; *Matthews et al.*, 2005a; *Fung et al.*, 2005; *Friedlingstein et al.*, 2006]. Observational studies have also provided evidence that carbon sinks may weaken as a result of climate changes; for example, the 2003 heat wave in Europe led to large reductions in terrestrial carbon uptake as a result of high temperatures and drought [*Ciais et al.*, 2005]. Furthermore, it has been shown that the effect of positive carbon-cycle feedbacks increases with the extent of simulated climate change, such that higher climate sensitivities (which themselves lead to warmer futures) result in stronger carbon-cycle feedbacks [*Govindasamy et al.*, 2005; *Andreae et al.*, 2005].

[4] Several studies have estimated equilibrium climate sensitivity (the long-term warming response to doubled CO_2) based on historical temperature observations; values between 2 and 4 degrees have been found to have the highest probabilities associated with them, though it has not been possible to eliminate the, albeit low, probability of climate sensitivities as low as 1 degree, or as high as 8 to 10 degrees [*Frame et al.*, 2005; *Forest et al.*, 2006; *Stainforth et al.*, 2005]. These probabilities have been used to estimate the probability of exceeding warming thresholds over the next century that may result in dangerous anthropogenic interference in the climate system [*Mastrandrea and Schneider*, 2004; *Schneider and Mastrandrea*, 2005; *Knutti et al.*, 2005]. However, the role of the carbon-cycle feedbacks in shaping future warming probabilities has only been assessed using simplified models [*Wigley and Raper*, 2001; *Knutti et al.*, 2003] which do not capture the effect of varying climate sensitivity on the strength of modelled carbon sinks.

[5] In this study, we use an intermediate complexity coupled climate-carbon model to quantify the effect of carbon-cycle feedbacks on probability distributions for warming over the next two centuries. The model used is the University of Victoria Earth System Climate Model (UVic ESCM) version 2.7 [*Weaver et al.*, 2001; *Matthews et al.*, 2005a], which includes an interactive carbon-cycle within a climate model comprised of coupled atmosphere, ocean, sea-ice, land, vegetation and carbon-cycle components. As such, this model includes the relevant interactions between climate change and the carbon-cycle, while retaining the flexibility and computational efficiency required to allow for repeated transient simulations with varying climate sensitivities. The model and experimental design are described in section 2. In section 3, we present the results of this study, showing the extent by which probability distributions of future warming are affected by the inclusion of an interactive carbon-cycle.

2. Methods

[6] The climate component of the University of Victoria Earth System Climate Model (UVic ESCM) consists of a

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general circulation 19-layer ocean model coupled to a dynamic-thermodynamic sea-ice model and a reduced-complexity single layer (energy-moisture balance) atmospheric model [*Weaver et al.*, 2001]. Horizontal resolution is 1.8 degrees latitude by 3.6 degrees longitude; water, heat and carbon are all conserved to machine precision without the use of flux adjustments. Land and terrestrial vegetation are represented by a simplified version of the Hadley Centre's MOSES2 land surface model coupled to the dynamic vegetation model TRIFFID [*Meissner et al.*, 2003; *Matthews et al.*, 2005b]. Ocean carbon is simulated by means of a OCMIP-type inorganic carbon-cycle model [*Weaver et al.*, 2001]; land carbon fluxes are calculated within MOSES2 and are allocated to soil and vegetation carbon pools within the five plant functional types supported by TRIFFID.

[7] We constructed an ensemble of 15 model versions for which the equilibrium climate sensitivity to CO_2 doubling varies from 1 to 8 degrees on 0.5 degree intervals. Each of these model versions was run from a common pre-industrial equilibrium to the year 2000, forced by observed atmospheric CO_2. From 2000 to 2200, the model was run twice for each climate sensitivity version: a coupled "feedback run," in which atmospheric CO_2 evolved freely in the model in response to a specified CO_2 emissions scenario; and, a "no-feedback run," in which the model was driven by a specified CO_2 stabilization scenario with concentrations asymptotically approaching 550 ppmv in 2150 [*Knutti et al.*, 2005]. The emissions scenario used to force the feedbacks runs was constructed so as to reproduce this CO_2 stabilization scenario in the absence of carbon-cycle feedbacks to climate; as such, the CO_2 concentrations (and resultant warming) between feedback and no-feedback experiments would have been identical were it not for the effect of carbon-cycle feedbacks.

[8] The methodology employed has been expanded from that used in previous carbon-cycle modelling studies [e.g., *Friedlingstein et al.*, 2006], which have simulated atmospheric CO_2 in paired "coupled" and "uncoupled" runs; this method allows for assessment of CO_2 differences (but not climate changes) that result from positive carbon-cycle feedbacks. The experiments presented here follow a novel 3-step methodology, capable of simulating both CO_2 and temperature differences resulting from carbon-cycle feedbacks. In step one, the model was forced from 2000 to 2200 by CO_2 concentrations from the 550-stabilization scenario discussed above. This was an "uncoupled" run (as defined by *Friedlingstein et al.* [2006]); atmospheric CO_2 increases were uncoupled from climate and as such there were no climate changes and thus no carbon-cycle feedbacks to climate. Emissions consistent with this run were calculated by summing changes in atmospheric CO_2, land and ocean carbon sinks. This diagnosed emissions scenario represents the allowable CO_2 emissions to stabilize CO_2 concentrations at 550 ppmv in the absence of positive carbon-cycle feedbacks.

[9] In the second step of our methodology, this emissions scenario was used to drive the coupled feedback runs described above, resulting in simulated atmospheric CO_2 and climate changes that reflect the effect of positive carbon-cycle feedbacks at each value of climate sensitivity. For the third step, the no-feedback runs were driven by the same atmospheric CO_2 concentrations used to generate the above emissions scenario, now with coupled atmospheric CO_2 and climate; these simulations produced the climate response to atmospheric CO_2 under varying climate sensitivities, but in the absence of carbon-cycle feedbacks. The difference in both atmospheric CO_2 and temperature changes between feedback and no-feedback runs represents the effect of carbon-cycle feedbacks at each value of climate sensitivity.

[10] In addition to positive carbon-cycle feedbacks, future CO_2 concentrations will be strongly affected by the direct response of terrestrial carbon uptake to elevated CO_2 (CO_2 fertilization). However, the magnitude of this future CO_2 fertilization effect is currently highly uncertain [e.g., *Körner et al.*, 2005; *Norby et al.*, 2005]. As with other biochemical vegetation models, MOSES2/TRIFFID simulates a substantial terrestrial carbon sink in response to elevated atmospheric CO_2 levels. To test the sensitivity of our results to this process in the model, CO_2 fertilization was removed in a second ensemble of simulations by holding atmospheric CO_2 constant at year-2000 levels (367.3 ppmv) with respect to the terrestrial vegetation model. The same emissions scenario (calculated by step one as described above) was used to generate a second feedback ensemble, without additional CO_2 fertilization after the year 2000. An equivalent no-feedback ensemble was constructed using CO_2 concentrations consistent with this emissions scenario in the absence of both carbon-cycle feedbacks to climate and future CO_2 fertilization.

[11] Since the UVic ESCM does not simulate atmospheric variability, inter-annual variability in the model is very small; as such, the deterministic nature of the model allows for probabilities associated with values for climate sensitivity to be assigned directly to warming outcomes from a single simulation. Modelled warming outcomes from each simulation were assigned probabilities corresponding to each model version's climate sensitivity; results from both feedback and no-feedback ensembles were treated equally, with paired versions of the model assigned equal probabilities. Probabilities of exceeding warming thresholds over the next two centuries were computed by calculating the area of the probability density distribution above a certain warming value relative to the area of the entire distribution.

3. Results and Discussion

[12] Simulated atmospheric CO_2 and global mean temperature from 2000 to 2200 are shown in Figure 1. In runs without carbon-cycle feedbacks (black line), atmospheric CO_2 concentrations followed the prescribed stabilization trajectory, while in the feedback runs (coloured lines), climate changes led to weakened carbon sinks and higher CO_2 concentrations (Figure 1a). Warming also increased with increasing climate sensitivity; in the case of the feedback runs (solid lines), the effect of increasing climate sensitivity was amplified by the effect of higher atmospheric CO_2 that resulted from increasingly positive carbon-cycle feedbacks. The effect of carbon-cycle feedbacks on simulated global warming ranged from virtually no additional warming at 2200 for a climate sensitivity of 1 degree to an additional warming of more than 2°C for a climate sensitivity of 8 degrees.

[13] In the ensemble of simulations without future CO_2 fertilization (shown on the right in Figure 1), year-2200

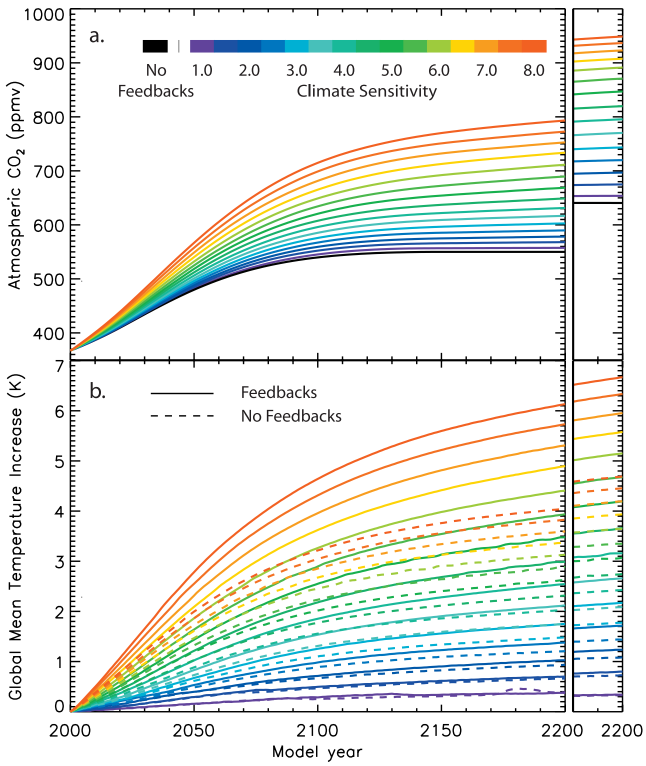

Figure 1. Atmospheric CO_2 and change in global-average surface temperature from 2000 to 2200. (a) Atmospheric CO_2 from the no-feedback runs (black line: stabilizing at 550 ppmv at the year 2150), and from the feedback runs (coloured lines) with increasing values of climate sensitivity resulting in higher atmospheric CO_2 concentrations. (b) Global mean temperature increase simulated by no-feedback (dashed lines) and feedback (solid lines) runs, with increased warming as climate sensitivity increased, and greater warming in the feedback run compared to the no-feedback run at any one value of climate sensitivity. At the right is shown an additional ensemble of simulations in which CO_2 fertilization was capped at present day.

CO_2 in the no-feedbacks runs was increased from 550 to 640 ppmv (in response to the same emissions scenario), with correspondingly higher CO_2 in all feedback runs. Despite higher CO_2, however, the effect on simulated warming over the next two centuries was small. The reason for this surprising result lies in dynamic vegetation responses to CO_2 fertilization. In the baseline model, CO_2 fertilization resulted in vegetation expansion, which decreased surface albedo and caused a small additional climate warming. When CO_2 fertilization was removed, this positive surface albedo feedback was also removed; as a result, the additional warming response to substantially higher atmospheric CO_2 was much smaller than might be expected.

[14] Using previous estimates of climate sensitivity probabilities, we have assigned probabilities to each of the trajectories plotted in Figure 1b. A probability distribution for global mean temperature increases over the next two centuries is shown in Figure 2, using probabilities for global mean climate sensitivity from *Hegerl et al.* [2006]. Figure 2a shows the probability density distribution for warming between 2000 and 2100 for runs with (red line) and without (blue line) carbon-cycle feedbacks. The median warming over the 21st century was increased by only about a quarter of a degree by the inclusion of carbon-cycle feedbacks. However, the effect of carbon-cycle feedbacks was substantial at higher values of climate sensitivity. For example, 4 degrees warming in the feedbacks ensemble had the same likelihood as 3 degrees warming in the no-feedbacks ensemble.

[15] Positive carbon-cycle feedbacks increased the probability of extreme future warming. The probability of exceeding warming thresholds over the next one to two centuries is shown in Figure 2b for both feedback (red) and no-feedback (blue) ensembles. When we included carbon-cycle feedbacks in our model simulations, the probability of exceeding 2°C warming by 2100 was increased from 10 to 23%; the probability of warming by more than 2°C by 2200 was increased from 23 to 41%. The probability of exceeding 3°C global mean temperature increase over the next 200 years was more than tripled.

[16] The specific probabilities reported above are dependent on the estimate of climate sensitivity used to assign

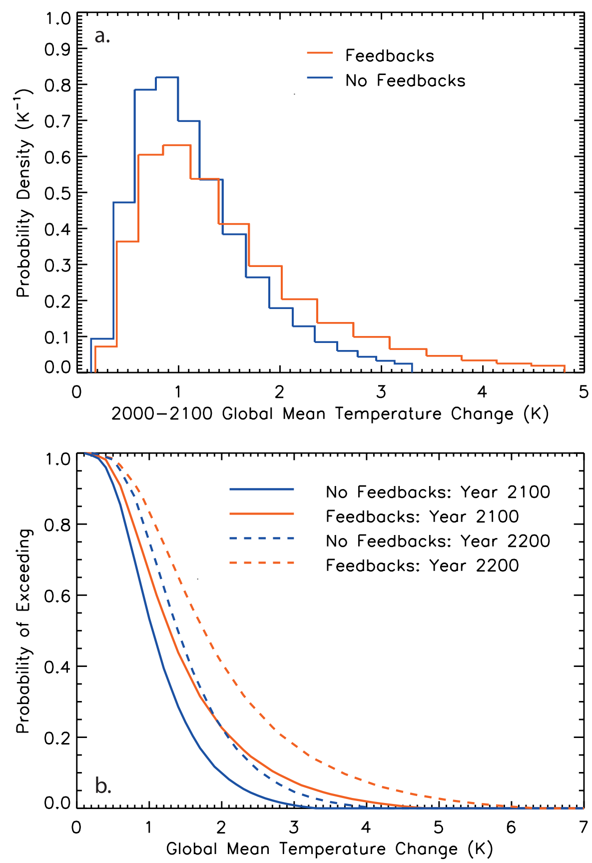

Figure 2. Probability distributions of future warming with and without carbon-cycle feedbacks. (a) Probability of global warming at 2100 relative to 2000 for feedback (red) and no-feedback (blue) runs. (b) Probability of exceeding warming values between 2000 and 2100 (solid lines) and between 2000 and 2200 (dashed lines) for feedback (red lines) and no-feedback (blue lines) runs. Probabilities are derived using the 'CH-Blend' estimate of the probability distribution of global mean climate sensitivity from *Hegerl et al.* [2006].

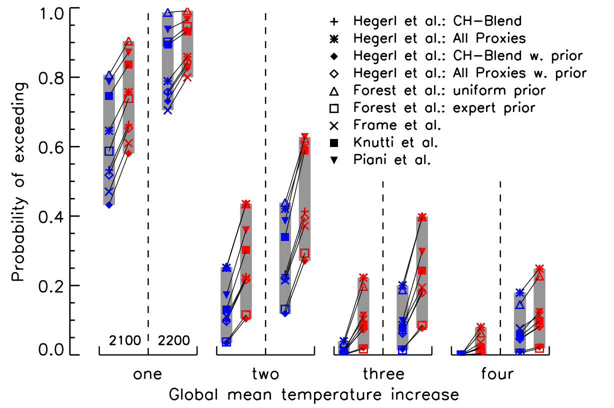

Figure 3. Probability of exceeding one, two, three, and four degrees global mean temperature increase over the next one to two centuries. Probabilities are computed using several of the latest probability distributions for climate sensitivity from the literature as indicated by the symbols [*Hegerl et al.*, 2006; *Forest et al.*, 2006; *Frame et al.*, 2005; *Piani et al.*, 2005; *Knutti et al.*, 2006]. For each pair of symbols joined by a thin solid line, the upper symbol (red) indicates results with carbon-cycle feedbacks, while the lower (blue) shows results without feedbacks. Results for 2100 (2200) are plotted to the left (right) of the dashed vertical line.

probability to modelled outcomes. Figure 3 shows the probability of exceeding one, two, three and four degrees warming by 2100 and by 2200 for both feedback and no-feedback ensembles, using several different estimates of climate sensitivity probabilities [*Hegerl et al.*, 2006; *Forest et al.*, 2006; *Frame et al.*, 2005; *Piani et al.*, 2005; *Knutti et al.*, 2006]. In general, probability distributions which assign higher probabilities to higher climate sensitivities also result in larger amplification of warming probabilities due to positive carbon-cycle feedbacks. Given the range of climate sensitivity distributions used here, carbon-cycle feedbacks increased the probability of exceeding 1 degree warming within this century by a factor of between 1.1 and 1.3, and of exceeding 2 degrees warming by a factor of between 1.7 and 3. The probability of exceeding 3 degrees was increased from a few percent to as much as 22%; in the case of exceeding 4 degrees warming by 2100, probabilities were increased from zero in the no-feedbacks runs to between 0.1 and 8 percent. At 2200, probabilities of exceeding 1, 2, 3, and 4 degrees were increased by factors in the ranges of 1–1.13, 1.4–2.3, 2.0–6.0 and 1.4–3.6, respectively.

[17] The probabilities reported here also depend on our choice of climate and carbon-cycle models, both of which represent reduced-complexity models which are ideally suited to capture the relevant climate/carbon-cycle interactions, as well as enable the large number of simulations required here. In this study, we have not accounted for inter-model differences in the carbon-cycle sensitivity to climate changes; that is, we have not included uncertainty in the strength of carbon-cycle feedbacks at a given rate of climate change. Including inter-model carbon-cycle differences (for example, as reported by *Friedlingstein et al.* [2006]) would introduce additional uncertainty in the effect of carbon-cycle feedbacks on future warming probabilities. However, the overall relationship between climate sensitivity, future warming and positive carbon-cycle feedbacks as demonstrated in this study is not model-dependent [*Andreae et al.*, 2005; *Friedlingstein et al.*, 2006]; for example, a similar plot to our Figure 2a was shown by *Knutti et al.* [2003], despite using a very different methodology, different emissions scenarios and a much simpler model than we have employed here. In addition, the methodology that we have developed here can serve as a template for further sensitivity studies as well as for simulations by other more comprehensive models.

[18] It is worth emphasizing that uncertainty in CO_2 fertilization does not have a large bearing on the effect of positive carbon-cycle feedbacks. Carbon-cycle feedbacks operate irregardless of CO_2 fertilization, and the specific probabilities we have reported here are only minorly sensitive to the strength of CO_2 fertilization in the model. Furthermore, while CO_2 fertilization uncertainty does affect the magnitude of future warming, the effect is reduced by the competing effects of carbon uptake and surface albedo changes. It is also important to note that a more comprehensive probabilistic estimate of future warming would require inclusion of uncertainties in ocean heat uptake as well as radiative forcing from both aerosols and non-CO_2 greenhouse gases. Using constant ocean mixing parameters in these simulations introduces a small positive bias as temperatures approach equilibrium, since high climate sensitivities are more consistent with higher ocean heat uptake [*Forest et al.*, 2006]. However, this bias is offset somewhat by the omission of aerosol and non-CO_2 greenhouse gas forcing, the combination of which is expected to contribute to additional warming over the next century [*Joos et al.*, 2001]. Furthermore, these biases apply equally to feedback and no-feedback ensembles; as such, the amplification of probabilities by carbon-cycle feedbacks is only minimally affected.

4. Conclusions

[19] These results are highly relevant to current efforts to predict the magnitude of global warming and the impacts of climate changes over the next two centuries. Although the inclusion of carbon-cycle feedbacks did not substantially alter the median expectation for future climate change resulting from this (quite restrictive) carbon emissions scenario, we found that carbon-cycle feedbacks substantially increased the probability of extreme warming, as indicated by the width of low-probability, high-consequence 'tails' of future warming probability distributions.

[20] We have shown this in the context of CO_2 stabilization at 550 ppmv; it is worth emphasizing that the effect of carbon-cycle feedbacks on the probability of extreme future warming would be much larger under a business-as-usual-type emissions scenario. This amplifying effect of carbon-cycle feedbacks is critical for the prediction of climate change impacts, which depend strongly on estimates of the probability of large climatic changes. Systematic analysis of carbon-cycle feedbacks is also directly relevant to efforts to stabilize levels of carbon dioxide in the atmosphere, whereby emissions targets aimed at a given stabilization level must be set with the recognition that future climate changes may substantially weaken natural carbon sinks [*Matthews*, 2005; *Jones et al.*, 2006]. Furthermore, we

argue that any analysis of the possibility of dangerous anthropogenic interference in the climate system must explicitly account for the role of carbon-cycle feedbacks as a potential amplifier of future climate warming.

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