How strong is carbon cycle-climate feedback under global warming?

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[1] The behavior of the coupled carbon cycle and physical climate system in a global warming scenario is studied using an Earth system model including the atmosphere, land, ocean, and the carbon cycle embedded in these components. A fully coupled carbon-climate simulation and several sensitivity runs were conducted for the period of 1860–2100 with prescribed IPCC-SRES-A1B emission scenario. Results indicate a positive feedback to global warming from the interactive carbon cycle, with an additional increase of 90 ppmv in the atmospheric CO_2, and 0.6 degree additional warming, thus confirming recent results from the Hadley Centre and IPSL. However, the changes in various carbon pools are more modest, largely due to the multiple limiting factors constraining terrestrial productivity and carbon loss. The large differences among the three models are manifestations of some of the poorly constrained processes such as the global strength of the CO_2 fertilization effect and the turnover time and rates of soil decomposition. *INDEX TERMS:* 0315 Atmospheric Composition and Structure: Biosphere/atmosphere interactions; 0330 Atmospheric Composition and Structure: Geochemical cycles; 1620 Global Change: Climate dynamics (3309). **Citation:** Zeng, N., H. Qian, E. Munoz, and R. Iacono (2004), How strong is carbon cycle-climate feedback under global warming?, *Geophys. Res. Lett.*, *31*, L20203, doi:10.1029/2004GL020904.

1. Introduction

[2] More than half of the anthropogenic CO_2 emission has been taken up by sinks in the ocean and over land [*Prentice et al.*, 2001]. The magnitude of future climate change depends critically on the behavior of these carbon sinks. One major feedback involves the change in these carbon sinks in response to climate change such as changes in temperature and precipitation patterns. Coupled carbon-climate modeling taking into account of such feedbacks from the Hadley Centre [*Cox et al.*, 2000; *Jones et al.*, 2003a, 2003b; *Betts et al.*, 2004] and IPSL [*Friedlingstein et al.*, 2001; *Dufresne et al.*, 2002; *Berthelot et al.*, 2002] showed large uncertainties in the predicted strength of carbon-climate feedback and its impact on climate prediction. For instance, the terrestrial carbon pools in these two models differ not only in magnitude but also in the direction. Here we present results from a fully coupled carbon-climate model and discuss the similarities and additional differences from the above two predictions.

2. Methods

[3] The physical climate components of the model consist of the global version of the atmospheric model QTCM [*Neelin and Zeng*, 2000; *Zeng et al.*, 2000], the Simple-Land model [*Zeng et al.*, 2000], and a slab mixed-layer ocean model with Q-flux to represent the effects of ocean dynamics [*Hansen et al.*, 1983]. The mixed-layer ocean depth is the annual mean derived from *Levitus et al.* [2000]. The terrestrial carbon model Vegetation-Global-Atmosphere-Soil (VEGAS [*Zeng*, 2003; N. Zeng et al., Mechanisms of interannual CO_2 variability, submitted to *Global Bigeochemical Cycles*, 2004]) is a dynamic vegetation model with full soil carbon dynamics. A box ocean carbon model is coupled to VEGAS through a well mixed atmosphere.

[4] The fully coupled carbon-climate model was run to a pre-industrial steady state (apart from high frequency internal variability) at year 1790. During this spinup process, the atmospheric CO_2 was nudged to an observed value of 281 ppmv so that the carbon pools and climate simulated are close to observations. The model was then run in a freely coupled mode from 1791 to 2100 (results analyzed for 1860–2100), with no other changing external forcing except for the anthropogenic CO_2 emission, taken from the IPCC-SRES A1B scenario. This run is referred to as the coupled run.

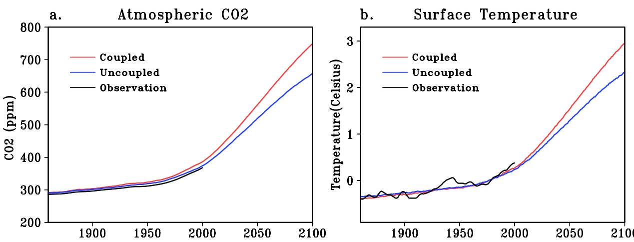

Figure 1. Atmospheric CO_2 (ppmv) (a) and surface temperature change (°C) (b) from 1860 to 2100, simulated by the fully coupled carbon-cycle climate model, with constant (pre-industrial) climate (blue), compared to observations. The surface temperature curve labeled uncoupled was obtained by an additional simulation where the CO_2 from uncoupled run was used to force the physical climate model, similar to conventional GCM global warming simulations.

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Table 1. Differences of the Atmospheric CO_2 (ppmv) and Surface Temperature (°C) Changes From 1860 to 2100 Between the Coupled Run and the Uncoupled Run

	ΔCO_2	ΔTs
UMD	90	0.6
Hadley	250	1.5
IPSL	75	0.6

[5] In order to delineate the effects of carbon-climate feedback, another run was conducted by using a constant CO_2 level of 281 ppmv in the longwave radiation module of the atmospheric model. Thus the carbon model sees a nearly constant climate without global warming, but carbon components are fully interactive including CO_2 fertilization effect and emission. This run is termed the uncoupled run. Such an experiment has been referred to as 'offline' simulation by *Cox et al.* [2000], 'prescribed climate' by *Dufresne et al.* [2002], and 'uncoupled' by *Friedlingstein et al.* [2003]. The difference between the coupled and the uncoupled run is an indicator of the strength of carbon-climate feedback.

3. Carbon-Climate Feedback

[6] Figure 1 shows the model simulated atmospheric CO_2 and global average surface temperature change from 1860 to 2100. By year 2000, the coupled run simulated 15 ppmv higher CO_2 compared to the observation, while the uncoupled CO_2 is very close to the observation. The surface temperature in the coupled run has risen by about 0.6°C, comparable to the observed overall warming. Since the multi-decadal surface temperature changes in the 20th century are likely caused by factors not considered here such as solar variability, aerosol and non-CO_2 greenhouse gases [*Stott et al.*, 2000; *Jones et al.*, 2003b], such level of agreement indicates a reasonably good representation of the past climate changes. During this historical period, our uncoupled run simulates a cumulative land sink of 28 PgC and an ocean sink of 178 PgC, which is stronger than the 100 PgC of the Hadley model [*Cox et al.*, 2000]. This strong ocean uptake partly compensates for our weak land sink such that CO_2 level at 2000 is only slightly higher than the observed value.

[7] At the end of the simulation (year 2100), atmospheric CO_2 reached a level of 658 ppmv in the uncoupled run, but the coupled run produced a CO_2 level of 748 ppmv, 90 ppmv higher. As a result, the coupled run surface temperature is 0.6°C higher. These results indicate a positive feedback from the interactive response of carbon cycle to climate change because the only difference in the two runs is the climate forcing for the carbon cycle, thus supporting the results from the Hadley Centre [*Cox et al.*, 2000] and IPSL [*Friedlingstein et al.*, 2001; *Dufresne et al.*, 2002].

[8] However, the magnitude of the change differs significantly among the three models (Table 1). Our model predicts about 90 ppmv additional CO_2 due to climate impact on the carbon cycle that implies a 0.6°C additional warming, while the Hadley model shows 250 ppmv more CO_2 and 1.5 degree additional warming. The IPSL model results are more similar to ours in terms of these changes, but other aspects differ greatly (below).

[9] Part of the differences is due to the different climate sensitivity to a given CO_2 change. For instance, our coupled run has a warming of about 3°C at year 2100, while it is 5.5°C for the Hadley model and 3°C for the IPSL model. These numbers are compounded with the strength of the carbon cycle feedback. In addition, the IPCC-SRES-A2 scenario used by IPSL has about 300 PgC larger cumulative emission than the IPCC-SRES-A1B scenario we used which is more similar to the IS92a used by Hadley. The difference in ocean carbon models are also partly responsible, especially given the simplicity of the box model we used. From 1860 to 2100, ocean in our coupled run absorbs 867 PgC, about 49% of the cumulative 1780 PgC emission, somewhat larger than the 700 PgC of IPSL model, and significantly larger than the 490 PgC of the Hadley model (Table 2). This is also in line with the weak land and strong ocean carbon sinks from 1860–2000. An elegant analysis by *Friedlingstein et al.* [2003] has shown that the major contribution comes from land in the Hadley and IPSL models. The main differences from our model also appear to be on land which we now focus our attention on.

4. Uncertainties in Land Carbon Response

[10] Figure 2 shows the evolution of the land carbon pool which consists of vegetation and soil carbon. In the uncoupled run, CO_2 fertilization leads to an increase in the net primary production (NPP) and subsequent accumulation of carbon in vegetation biomass. This drives an increase in soil carbon as vegetation-to-soil turnover also increases. The total increase in land carbon from 1860 to 2100 is about 100 PgC with 60 PgC from vegetation, 40 PgC from soil (Table 2).

[11] A remarkable reversal of soil carbon uptake is seen in the coupled run where the soil has released 40 PgC at 2100. Although vegetation carbon increased, but it has saturated at 20 PgC at 2100. The less vegetation uptake compared to the uncoupled run is partly due to warming-enhanced maintenance cost (autotrophic respiration), partly due to change in precipitation pattern. This modest increase in vegetation carbon (therefore turnover) is not enough to counteract the enhancement of respiration loss in soil at higher temperature. As a result, land has become a net CO_2 source of 20 PgC to the atmosphere at the end of the simulation.

[12] Such a divergence in land carbon response with or without climate-carbon feedback (120 PgC difference in the

Table 2. Change in the Carbon Pools (2100 Minus 1860) From Three Coupled Carbon-Climate Models (PgC)

	Uncoupled				Coupled				Difference			
	Vege	Soil	Land	Ocean	Vege	Soil	Land	Ocean	Vege	Soil	Land	Ocean
UMD	60	40	100	866	20	−40	−20	867	−40	−80	−120	1
Hadley	220	410	630	370	60	−150	−90	490	−160	−560	−720	120
IPSL	380	300	680	670	310	170	480	700	−70	−130	−200	30

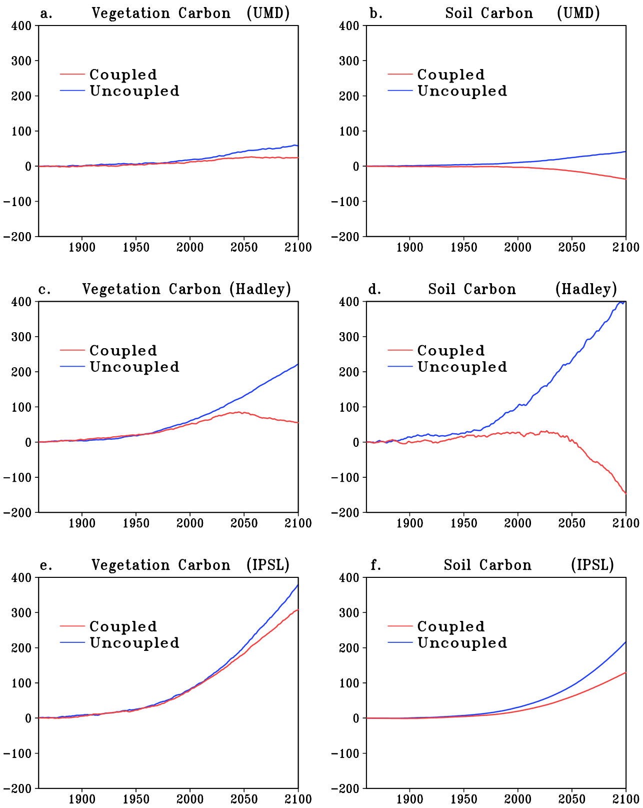

Figure 2. Vegetation and Soil carbon change in PgC since 1860 for the fully coupled run and uncoupled run from the present model (UMD, upper panels), the Hadley Centre (middle panels), and IPSL (lower panels).

two runs) is also seen in the Hadley Centre results, but their amplitude is 720 PgC, 6 times larger than ours (Table 2). The IPSL difference between the two runs (200 PgC) is more similar to ours, but they differ from ours and Hadley's in that their growth enhancement significantly outcompetes the climate change impact on respiration rate so that in the coupled run both soil and vegetation pools continue to increase over time.

[13] The spatial pattern of the land carbon change (Figure 3) indicates that uncoupled run has an increase of carbon accumulation everywhere due to CO_2 fertilization effect. The coupled run shows intriguing spatial variations. At high latitude regions in Canada, Scandinavia and northern Siberia, the coupled run shows increase in carbon storage larger than the uncoupled run due to enhanced growth in these currently temperature-limited regions, which outcompetes the increased respiration loss at higher temperature. However, at middle and low latitudes, increased soil decomposition rate and autotrophic respiration at higher temperature dominate the CO_2 fertilization effect, leading to less carbon storage. This is somewhat complicated by the change in precipitation which tends to have high spatial variation. Increase in precipitation (not shown) is responsible for the carbon increase in regions such as parts of northern Amazon and West Africa. Such precipitation pattern is somewhat different from the Hadley Centre model where a perpetual El Nino like state gave rise to a reduced rainfall and vegetation dieback in the Amazon [*Betts et al.*, 2004]. Because our model does not have ocean dynamics, and climate models also differ widely in regional responses, such regional comparisons should only be viewed with great caution.

5. Sensitivities and Discussion

[14] In order to understand the large differences among the three models, we conducted the following three sensitivity experiments with different model parameterizations from the standard run described above:

[15] 1. Stronger fertilization by double the sensitivity of photosynthesis to CO_2;

[16] 2. Single soil pool by lumping the three soil carbon pools (fast, intermediate and slow) into one, with a turnover time of 25 years at 25°C, a value somewhat slower than the standard run's fast soil pool, but much faster than the intermediate (80 years) and the slow soil pool (1000 years);

[17] 3. Higher soil decomposition rate dependence on temperature for the lower two soil layers (Q_{10} = 2.2).

[18] The results from the coupled runs for these three experiments together with the standard run are shown in Figure 4. A stronger fertilization effect increases growth significantly so that land is still a sink of 150 PgC in 2100, unlike the 20 PgC source in the standard run, but in the direction of the IPSL result. The single soil layer experiment shows that land becomes a carbon source of 100 PgC, much larger than the standard run, but similar to the Hadley

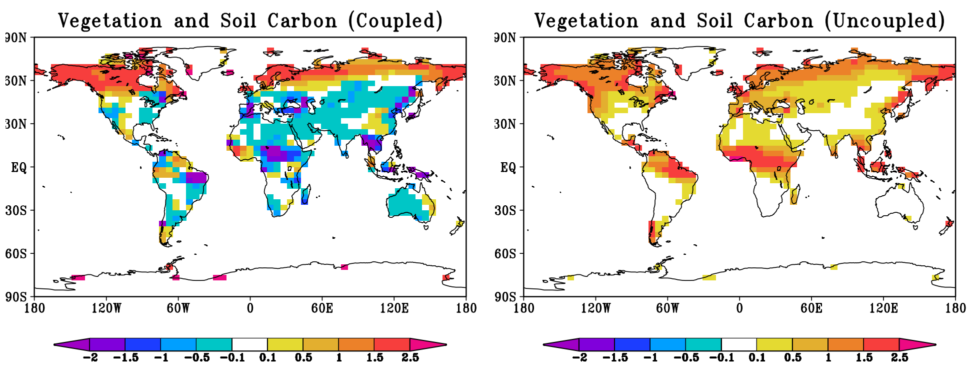

Figure 3. Spatial distribution of total land carbon (vegetation + soil) change for the coupled and uncoupled runs. These are the differences between the last 30 years (2071–2100) and the first 30 years (1860–1889), showing different behavior at high latitude and mid-low latitude regions. In kg m^{-2}.

Center result. Thus, the differences in representing these two processes may be the key behind the large uncertainties among the three models.

[19] Our two lower soil pools have weaker temperature dependence of decomposition due to physical protection underground (Q_{10} value of 2.2 for the fast pool, 1.35 for the intermediate pool, and 1.1 for the slow pool). Higher temperature sensitivity would be expected to increase soil carbon release under global warming [*Jones et al.*, 2003a]. We were thus surprised not to see this high sensitivity in the third experiment with Q_{10} value of 2.2 also for the two slower soil pools. This is because the turnover time in these two pools, especially the slow soil pool, are comparable or longer than the 100 year time scale considered here for global warming, and thus their full potential of carbon release has not been realized by the year 2100. In contrast, the single soil layer experiment has a fast turnover time for all the soil carbon, thus a near-equilibrium response to the warming.

[20] Current observations have not converged on the strength of CO_2 fertilization on global scale [*Field*, 2001]. While models often rely on strong CO_2 fertilization to explain the 'missing carbon sink' of 1–2 PgC y^{-1} observed in the 1980–90s [*Prentice et al.*, 2001], the weak dependence in our model produces only a small land CO_2 sink of 0.5 PgC y^{-1} in the uncoupled run, 0.2 PgC y^{-1} in the coupled run (partly due to warming-induced soil carbon release). However, our model, as well as those of Hadley and IPSL, do not consider effects such as land use change and fire suppression, which may be important contributors to be considered in future coupled modeling. In addition, the slower soil pools may not respond to global warming as fast, and their temperature dependence may not be as strong as the surface soil and litter. Our sensitivity experiments suggest a significant impact of these uncertainties.

[21] Although all models agree on a positive carbon cycle feedback as indicated by all negative values in Table 3, the predicted difference between coupled and uncoupled runs for our strong fertilization case is −80 PgC, compared to −120 PgC in the standard case, both are modest, similar to IPSL (−200 PgC). The difference is −260 PgC in the one soil layer runs, more than doubled from the standard case, and closer to, but still significantly smaller than in the Hadley model (−720 PgC). This is in addition to the differing land carbon changes among the coupled runs (Figure 4). These results suggest that different CO_2 fertilization strengths explain part of the UMD-IPSL differences (and the UMD-Hadley difference in the uncoupled runs), and soil decomposition and turnover time explain partly the UMD-Hadley differences in the coupled runs. Thus, in order to narrow down uncertainties in the prediction of future carbon and climate change in projects such as the Coupled Carbon Cycle Climate Model Intercomparison Project (C4MIP [*Fung et al.*, 2000], it is urgently needed to improve our knowledge of some major issues in the modern carbon cycle including the global strength of CO_2 fertilization effect, the 'missing carbon sink', and the turnover time and decomposition rate of the slower soil pools.

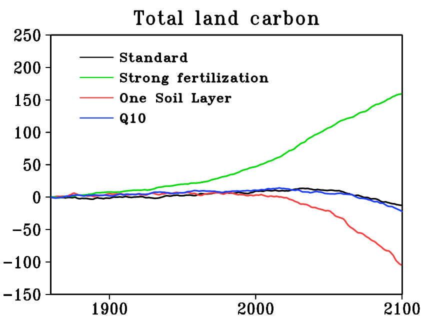

Figure 4. Total land carbon change (PgC) since 1860 in four fully coupled runs: the standard run (same run as in Figure 2 and three sensitivity experiments: strong CO_2 fertilization effect, single soil layer, and high soil decomposition rate dependence on temperature (Q_{10} = 2.2 for all soil layers, blue).

Table 3. Difference in Total Land Carbon Pool (PgC) Between Coupled and Uncoupled Runs at Year 2100 for Various Simulations

UMD Standard	UMD Strong Fertilization	UMD One Soil Layer	UMD All Q10=2.2	Hadley	IPSL
−120	−80	−260	−130	−720	−200

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