HOW POSITIVE IS THE FEEDBACK BETWEEN CLIMATE CHANGE AND THE CARBON CYCLE ?

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ABSTRACT

Future climate change induced by atmospheric emissions of greenhouse gases is believed to have a large impact on the global carbon cycle. Several offline studies focusing either on the marine or on the terrestrial carbon cycle highlighted such potential adverse effects. Two recent online studies, using ocean-atmosphere general circulation models coupled to land and ocean carbon cycle models, investigated in a consistent way, the feedback between the climate change and the carbon cycle. These two studies used observed anthropogenic CO_2 emissions for the 1860-1995 period and IPCC scenarios for the 1995-2100 period to force the climate-carbon cycle models. The study from the Hadley Centre group, showed a very large positive feedback, atmospheric CO_2 reaching 980 ppmv by 2100 if future climate impacts on the carbon cycle, but only about 700 ppmv if the carbon cycle is assumed to be insensitive to the climate change. The IPSL coupled climate-carbon cycle model, simulated a much smaller positive feedback: climate impact on carbon cycle leads by 2100 to an addition of less than 100 ppmv in the atmosphere. Here, we perform a detailed feedback analysis to show that such differences are due to two key processes that are still poorly constrained in these coupled models, first Southern Ocean circulation which primarily controls the geochemical uptake of CO_2, and second vegetation and soil carbon response to global warming. Our analytical analysis reproduces remarkably the results obtained by the fully coupled models. Also it allows us to identify, that amongst the two processes mentioned above, the last one, the land response to global warming is the one that essentially explains the differences between the IPSL and the Hadley results.

1. Introduction

Increased atmospheric CO_2 due to anthropogenic emissions may lead to significant climate change in the coming century (Houghton, 2001). Both elevated CO_2 and climate change have an impact on land and ocean carbon cycle. Several previous studies investigated the impact of climate change on either the land or the ocean carbon uptake, and generally found it to be negative (eg., Cao and Woodward, 1998, Cramer et al., 2001, Sarmiento and LeQuere, 1996., Sarmiento et al., 1998, Joos et al., 1999). However, in order to be fully consistent, one has to study simultaneously both the climate system and the global carbon cycle. This is the only way to properly account for the potentially large feedbacks between these two systems. Such analysis has been performed by two groups from Hadley Centre, U.K. (Cox et al., 2000) and from IPSL (Dufresne et al., 2001) in the context of historical and future climate change, using IPCC CO_2 emission scenarios. In this paper, we summarize these two studies, highlighting the main mechanisms responsible for the differences between the Hadley Centre and the IPSL results.

2. Methodology

Both groups used a similar methodology, coupling ocean-atmosphere general circulation models (OAGCMs) to land and ocean carbon cycle models (references for the GCMs can be found in Cox et al., (2001) and in Dufresne et al., (2002) for Hadley and IPSL respectively). The OAGCMs generate the climatic fields for the carbon models that calculate the land and ocean uptakes of CO_2. Atmospheric CO_2 is calculated as the balance between anthropogenic emissions and the sum of land and ocean fluxes. The Hadley Center group uses the IPCC-IS92a emission scenario, while IPSL uses the IPCC-SRES-A2 scenario (Nakicenovic et al., 2000). These two scenarios are identical for the historical period (1860-1995) and differ for the future (1995-2100). Accumulated emissions amount to 1900 GtC for Hadley and to 2200 GtC for IPSL. Both groups make the following simplifying assumptions: sulfates aerosols emissions are ignored, land use change is not accounted for in the land surface model, nitrogen and other nutrient/toxic deposition on land and ocean are ignored. However, The Hadley models accounts for non-CO_2 greenhouse gases emissions while IPSL model does not. Also, the land surface scheme of the Hadley model accounts for vegetation dynamics, the IPSL model does not, vegetation distribution being held at present-day value.

Each group performed three runs:

a) a control coupled run with no anthropogenic emission, hereafter referred as control run

b) a coupled run with IPCC emissions, leading to increased CO_2 and climate change, hereafter referred as coupled run

c) an uncoupled run with the same IPCC emissions, but the climate from the control run, hereafter referred as uncoupled run. In this last run, the carbon cycle is affected by the increased atmospheric CO_2 but does not see any climate change.

Mathematically, the atmospheric CO_2 (expressed in GtC here) in each of these runs is respectively calculated as

a) $$CO2_t^{ctrl} = CO2_{t-1}^{ctrl} - F_{AO}^{0} - F_{AB}^{0} \tag{1}$$

b) $$CO2_t^{cou} = CO2_{t-1}^{cou} + F_{IPCC} - F_{AO}^{cou} - F_{AB}^{cou} \tag{2}$$

c) $$CO2_t^{unc} = CO2_{t-1}^{unc} + F_{IPCC} - F_{AO}^{unc} - F_{AB}^{unc} \tag{3}$$

where F_{IPCC}, are the IPCC scenario emissions of CO_2 (in GtC/yr), $F_{AO}^{o}, F_{AO}^{cou}, F_{AO}^{unc}$ ($F_{AB}^{o}, F_{AB}^{cou}, F_{AB}^{unc}$) are atmosphere-ocean (atmosphere-land) fluxes of CO_2 for respectively the control, coupled and uncoupled runs.

3. Main results

Both models simulate climate and CO_2 evolution for the period 1860-2100. Despite the neglect of important climatological forcing factors (such as other GHGs and sulphate aerosols) the IPSL model does a good job of reproducing the observed rise in atmospheric CO_2 and temperature for 1860-2000. The Hadley model overestimates both global warming and CO_2 increase by the current day, producing a CO_2 concentration of 395ppmv (as opposed to the observed 375ppmv) and a temperature rise of 1.0K (as opposed to the observed 0.5K). This overestimate of historical warming is consistent with the neglect of sulphate aerosols which are believed to have masked a significant part of the positive radiative forcing due to greenhouse gases (Mitchell et al., 1995). A more recent Hadley Centre run including sulphate aerosols, solar variability and tropospheric ozone changes is able to reproduce the observed increases in temperature and CO_2 (within the error bars on the net land-use emissions). This experiment produces a similar positive feedback in the future because anthropogenic sulphate aerosols are predicted to reduce sharply through the 21st century. In this study we choose to stay with the original published (greenhouse gases only) Hadley Centre runs (Cox et al., 2000) in order to simplify the intercomparison, and because this is not likely to affect our overall conclusions regarding the reasons for the different Hadley and IPSL projections to 2100.

In the absence of climate-change the two models produce remarkably similar CO_2 increases despite using different emissions scenarios (figure 1). Although the scenarios are identical to the current day, the SRES A2 emissions used by IPSL reaches about 29 GtC/yr by 2100, as opposed to about 20 GtC/yr in the IS92a scenario used by Hadley. The fact that the uncoupled models produce similar CO_2 projections indicates that their uptake rates differ substantially even in the absence of climatic feedbacks. However, the real differences emerge once climate-carbon cycle feedbacks are enabled in the two models. By 2100 the atmospheric CO_2 concentrations have reached 980 ppmv and 780 ppmv, in the Hadley Centre and IPSL models respectively. Although the two models simulate a positive feedback (higher CO_2) when climate and carbon cycle are coupled, the magnitude of the climate-carbon cycle feedback is dramatically different in these models. In the remainder of this paper we set out the reasons for this difference.

4. Feedback Analysis

As climate and carbon cycle form an intimately coupled system it is hard to disentangle the processes responsible for the differences between the Hadley and the IPSL coupled models behavior. To do so, we perform a feedback analysis for the two models, following the methodology of Hansen. et al., (1984). The coupling between the carbon cycle and the climate system can be linearized by the following set of equations:

$$\Delta CO2 = \int_0^t F_{IPCC} - \Delta F_{AO} - \Delta F_{AB} \quad (4)$$

$$\Delta T = \alpha \Delta CO2 + \Delta T_{ind} \quad (5)$$

with $\Delta F_{AO} = \beta_{AO} \Delta CO2 + \gamma_{AO} \Delta T$, and $\Delta F_{AB} = \beta_{AB} \Delta CO2 + \gamma_{AB} \Delta T$ (6)

ΔT_{ind} being the climate change due to any other forcing that CO_2 (eg. other greenhouse gases, ozone, aerosols, solar variability,…). With the definition of equations (6), one can easily redefine the atmosphere-ocean CO_2 fluxes as:

$F_{AO}^{cou} = F_{AO}^{0} + \beta_{AO} \Delta CO_2{}^{cou} + \gamma_{AO} \Delta T$ and $F_{AO}^{unc} = F_{AO}^{0} + \beta_{AO} \Delta CO_2{}^{unc}$ (7a)

and similarly for the atmosphere-land fluxes:

$F_{AB}^{cou} = F_{AB}^{0} + \beta_{AB} \Delta CO_2{}^{cou} + \gamma_{AB} \Delta T$ and $F_{AB}^{unc} = F_{AB}^{0} + \beta_{AB} \Delta CO_2{}^{unc}$ (7b)

Now, one can introduce equation (6) in (4), and then (4) in (5) to give :

$$\Delta T = 1/(1-g)\, \Delta T_{unc} \quad (8a)$$

or similarly, by introducing (5) in (4):

$$\Delta CO2 = 1/(1-g)\, \Delta CO2_{unc} \quad (8b)$$

where $g = -\alpha(\gamma_{AO} + \gamma_{AB})/(1 + \beta_{AO} + \beta_{AB})$ (9)

is the gain of the feedback and ΔT_{unc} ($\Delta CO2_{unc}$) is the change in temperature (atmospheric CO_2) in the uncoupled system (i.e if γ_{AO} and γ_{AB} are null). The ratio $1/(1-g)$ is usually named the net feedback factor, f (Hansen et al., 1984)

From equation 9, one sees that the climate-carbon cycle gain is larger if:

- α , the GCM temperature sensitivity to CO_2 is large,
- γ_{AO} (γ_{AB}), the ocean (land) carbon uptakes sensitivity to climate change is negative and large,
- β_{AO} (β_{AB}) the geochemical sensitivity of the ocean (land) carbon uptake to CO_2 is low.

In the following sections, we estimate each of these factors for the Hadley and for the IPSL simulations in order to assess their contributions to the large difference in the overall feedback magnitude of the two models.

4.1 GCM Sensitivity to CO_2

We analyzed the surface temperature warming for each climate model as a function of each model atmospheric CO_2. The Hadley GCM shows a slightly larger α, the climate sensitivity to CO_2, than the IPSL (Figure 2). However this can easily be explained by the difference in the forcing applied to the models. although none of the models account for change in aerosol emissions, Hadley model accounts for both CO_2 and non-CO_2 emissions (CH_4, N_2O,…) whereas IPSL only accounts for CO_2. Therefore, it is normal that for the same atmospheric CO_2 level, the Hadley warming is larger than the IPSL warming (as its CO_2 equivalent level will be higher). If the warming was expressed as a function of radiative forcing, the two models would give close results. This sensitivity to CO_2 alone is the number which should enter the sensitivity calculation.

4.2 Carbon Cycle Sensitivity to CO_2 alone

Here we analyze the two uncoupled simulations from Hadley and IPSL where the atmospheric CO_2 increase affects the carbon cycle but does not affect the climate, i.e. the carbon cycle models are driven by the climate fields from the control runs. The striking figure from Figure 3. is the difference in the ocean uptake between the two models for a given atmospheric CO_2. As this analysis is performed on the uncoupled simulations, the blame can not be put on climate change impact on oceanic circulation, it is the circulation from the control climate which as to explain the difference. We find that the ocean carbon component of the Hadley model shows a much lower carbon flux sensitivity to CO_2 alone (βao) than the IPSL model. At 700 ppmv, the Hadley geochemical oceanic uptake amounts to 4 GtC/yr, while the IPSL uptake reaches 8 GtC/yr. That means that for a given amount of CO_2 released to the atmosphere, the fraction remaining in the atmosphere (the airborne fraction) will be much larger in the Hadley model. When looking at the spatial pattern responsible for such a large difference in oceanic uptake (Figure 4) one clearly see that the CO_2 uptake in the Southern ocean is about twice as large in the IPSL run than in the Hadley run. Higher oceanic convection at these latitudes explain the larger uptake of the IPSL ocean model. Offline ocean simulations of CFCs and anthropogenic CO_2 historical invasion performed within the OCMIP (ocean carbon cycle model intercomparison project) framework previously highlighted that Southern Ocean is one of the regions where differences amongst models are the largest (Dutay et al., 2001, Orr et al., 2001). Recent studies show that even for the present-day CO_2 budget, the role of the Austral ocean is merely known. Recent measurements (Metzl et al., 2001) as well as atmospheric inversion (Gurney et al., 2002, Roy et al., 2001) and oceanic inversions (Gruber et al., 2001) and common estimates from Takahashi et al., (1999) are still in contradiction. Here we show that this uncertainty in Southern Ocean activity needs to be resolved as it translates in the future into a very large uncertainty in atmospheric CO_2 and hence global warming.

4.3. Carbon Cycle Sensitivity to climate change

Finally, we calculate the land (ocean) carbon cycle sensitivity to climate change as the difference between the land (ocean) carbon flux from the coupled run and from the uncoupled run. The land carbon component of the Hadley model shows a slightly more negative γab, the carbon flux sensitivity to climate than the IPSL model. This feature was already mentioned in Dufresne et al., (2001). This is mainly due to difference in the vegetation and soil carbon dynamic. In the uncoupled run, the Hadley model has a large carbon allocation to the soil compartment, while IPSL stores mainly carbon in the living vegetation. The warming that occurs in the coupled run induces a larger and worldwide soil carbon release in the Hadley framework, a pattern mainly confined in the tropics in the IPSL simulation. There is little data to validate or invalidate these results. The Free-Air CO_2 Enrichment (FACE) experiments explored the ecosystem level response to enhanced CO_2. These data show that forest ecosystems have enhanced growth rate under elevated CO_2 (25% increase for a 200 ppmv increase in atmospheric CO_2) (DeLucia et al., 1999) but still reduced increase in soil carbon (Schlesinger and Lichter, 2001). However, these results were obtained after only 2 years of fumigation and under constant high CO_2. Therefore they are hard to extrapolate in our context.

Regarding the ocean both models have a positive γao, the sensitivity of the ocean carbon uptake to climate change, i.e. in the coupled run the oceanic uptake is larger than in the uncoupled run. However this is essentially because of the larger atmospheric CO_2 content in the coupled run than in the uncoupled run (see equations 7a and 7b). The higher atmospheric CO_2 induces an indirect enhancement in the ocean geochemical uptake of CO_2 that offsets the direct negative impact of climate change (enhanced ocean stratification) on oceanic carbon uptake. The climate effect alone would reduce the ocean uptake in the two models (see Table 1).

4.4. Analytical estimate of the feedback

Using equation 9, we can now estimate the gain of the climate-carbon cycle feedback for both Hadley and IPSL simulations. From Figures 2, 3 and 5, we can derive the terms α, βab, βao, γab, and γao and then calculate g and f terms for both models (Table 1). For this analytical calculation, we corrected the γab and γao for the indirect effect of climate change on carbon uptake due to enhanced atmospheric CO_2. We find values for the gain g of 0.166 and 0.41 for IPSL and Hadley models respectively. This translates into a feedback factor, f, of 1.2 and 1.69 respectively. This numbers are very close to the overall feedback factor that can be derived from Figure 1, by comparing the atmospheric CO_2 in 2100 from the coupled and uncoupled simulations. Indeed for IPSL, atmospheric CO_2 increases by 494 ppmv in the coupled run vs. 414 ppmv in the uncoupled run, that is to say, an amplification of 1.19. For the Hadley simulations, the numbers are 692 ppmv vs. 413 ppmv, that is to say, an amplification of 1.675.

The remarkably close agreement between our analytical estimate and the observed estimate (from Figure 1) demonstrates that our feedback analysis is capturing all the important processes and that the linear perturbation assumption still holds for both simulations, i.e. that the changes are small enough to ignore higher orderm terms. Our analytical feedback calculation clearly shows that differences between the Hadley and IPSL coupled runs are not due to differences in the forcing scenarios (IPCC scenario of CO_2 emissions) but rather to large differences in the model sensitivities (Table 1): the land carbon sensitivity to climate and the ocean carbon sensitivity to CO_2.

Using our equations, we can also estimate what is the importance of a given model component in the coupled system. For example we can calculate to the first order what atmospheric CO_2 level the Hadley model would reach if it had the IPSL ocean carbon cycle (and its driving circulation) and vice versa for the

IPSL model with the Hadley ocean. Using the βao from IPSl in the Hadley framework would reduces the Hadley gain to 0.36, which would translate into a 2100 atmospheric CO_2 concentration of 925 ppmv (instead of 980 in the coupled Hadley simulation). Doing the same for the IPSL model, that is, using the βao from Hadley, would increases the IPSL gain to 0.19, which translates into an atmospheric CO_2 concentration of 795 ppmv (that is only 15 ppmv higher than in the coupled IPSL simulation).

Doing the similar calculation with the land component gives more dramatic results. Indeed using the land carbon cycle sensitivity to climate, γab, of IPSL in the Hadley framework would lower the gain down to 0.21, translating into a atmospheric concentration of 810 ppmv (that is 170 ppmv less than in the Hadley coupled simulation, and only 30 ppmv higher than what obtained in the IPSL coupled runs). The IPSL model with the Hadley γab leads to a gain of 0.31 and an atmospheric CO_2 of 886 ppmv (more than 100 ppmv higher than in the IPSL coupled simulation). It is then clear that, although the strength of the oceanic geochemical uptake is a non negligeable term, the dominant factor is the climate sensitivity of the land carbon model. A calculation of the total derivative of the gain equation (equation 9), given in the Appendix confirms this results, the main term driving the difference between the Hadley and the IPSL runs is γab.

5. Conclusions

In this study, we compared the response of two climate models coupled to carbon cycle models and forced by CO_2 emissions scenarios for the 1860-2100 period. Both Hadley and IPSL models simulate that global warming will reduce the efficiency of the carbon cycle to store anthropogenic CO_2, inducing a positive feedback in the climate-carbon cycle system. However, the magnitude of that positive feedback varies by more than a factor of 2 between the models. We performed a feedback analysis in order to identify what processes are responsible for such an important difference. Three sensitivity parameters are controlling the amplitude of the climate-carbon cycle feedback, the climate sensitivity to CO_2, the carbon cycle sensitivity to CO_2 and the carbon cycle sensitivity to climate change. Here we showed that the difference between the Hadley and the IPSL simulation results from two factors:

- the Hadley model has a more negative land carbon sensitivity to climate, mainly because of faster cycling of carbon through the living biomass.
- the IPSL model has a much larger ocean carbon sensitivity to CO_2, essentially because of much stronger vertical mixing in the Southern Ocean.

That means that for a given emission scenario, compared to the IPSL, the atmospheric CO_2 will be higher in the Hadley configuration, as its geochemical ocean uptake is much lower. That translates in a larger climate change, which has an even larger impact on the terrestrial carbon cycle, as its sensitivity to climate change is much larger.

However our substitution analysis clearly shows that the difference in the climate impact on the land carbon cycle is mainly responsible for the large difference in the overall response of the two models.

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Appendix

The total derivative of *g* is:

$$\Delta g = \frac{\partial g}{\partial \alpha}\Delta\alpha + \frac{\partial g}{\partial \gamma}\Delta\gamma + \frac{\partial g}{\partial \beta}\Delta\beta \qquad \text{(A1)}$$

using equation 8 we can calculate the partial derivatives:

$$\frac{\partial g}{\partial \alpha} = -\gamma/(1+\beta) \qquad \text{(A2)}$$

$$\frac{\partial g}{\partial \gamma} = -\alpha/(1+\beta) \qquad \text{(A3)}$$

$$\frac{\partial g}{\partial \beta} = \alpha\gamma/(1+\beta)^2 \qquad \text{(A4)}$$

For clarity, we grouped here γ_{AO} and γ_{AB}, in one single term γ , the overall carbon cycle sensitivity to climate change, the same being done for β , the overall carbon cycle sensitivity to CO_2. From Table 1, we can estimate the partial derivatives (equations A1, A2 and A3) for IPSL, that amounts respectively to 23 ppmv/K, $1.3e^{-3}$ K/GtC, and $3.e^{-2}$ ppmv/GtC. Therefore, a 10% uncertainty in the estimation of α , γ, and β from the IPSL value will translate into an uncertainty in the estimate of *g* of 0.017, 0.017, and 0.01 respectively. So the *g* sensitivity to α and γ is slightly larger than the *g* sensitivity to β .Moreover, when looking at the differences in the Hadley and IPSL estimates of α , γ, and β , we see that the largest uncertainty is in the estimate of γ (overall γ for Hadley is 75% larger than for IPSL). That difference in γ alone explains a difference of 0.13 between the Hadley and IPSL estimates of *g*, while differences in the Hadley and IPSL estimates of α and β both translate in differences in the estimate of *g* lower than 0.05. This sensitivity analysis confirms the results found in section 4.4, that the mechanism mainly responsible for the very different behavior of the Hadley and IPSL coupled models is the land carbon cycle response to climate change.

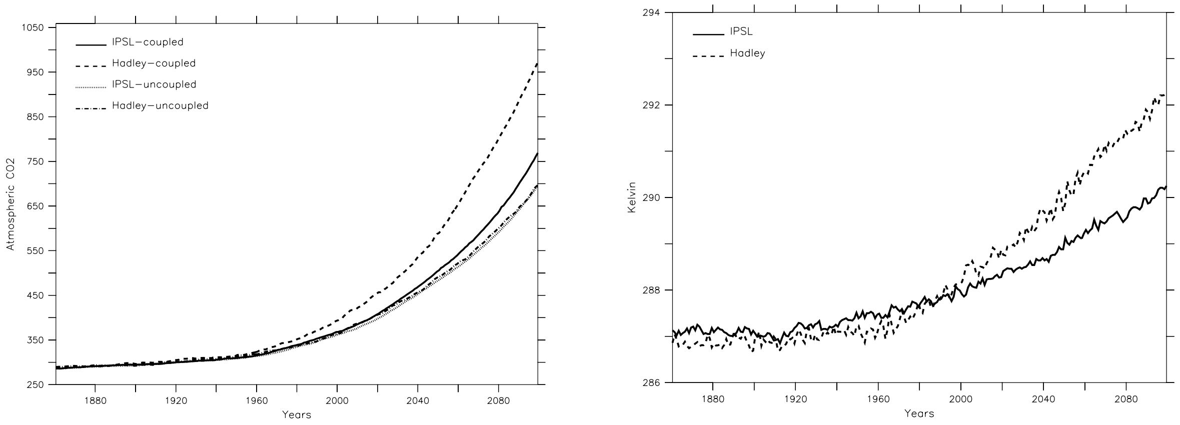

Fig. 1 (a) Calculated atmospheric CO_2 and (b) surface temperature for the IPSL (solid line) and Hadley (dashed line) coupled runs. Atmospheric CO_2 obtained in the Hadley and IPSL uncoupled runs are also shown on figure 1a.

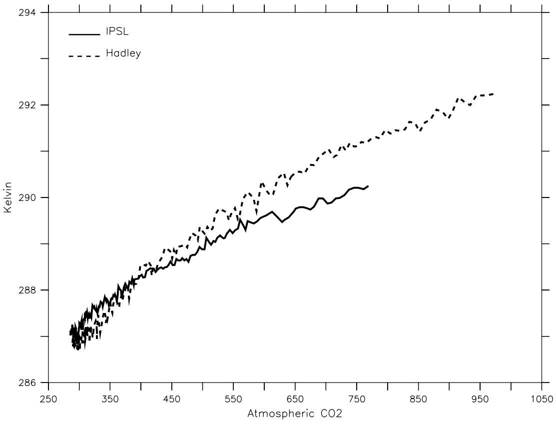

Figure 2. Climate sensitivity (surface warming as a function of atmospheric CO_2) for IPSL (solid line) and Hadley (dashed line) coupled models.

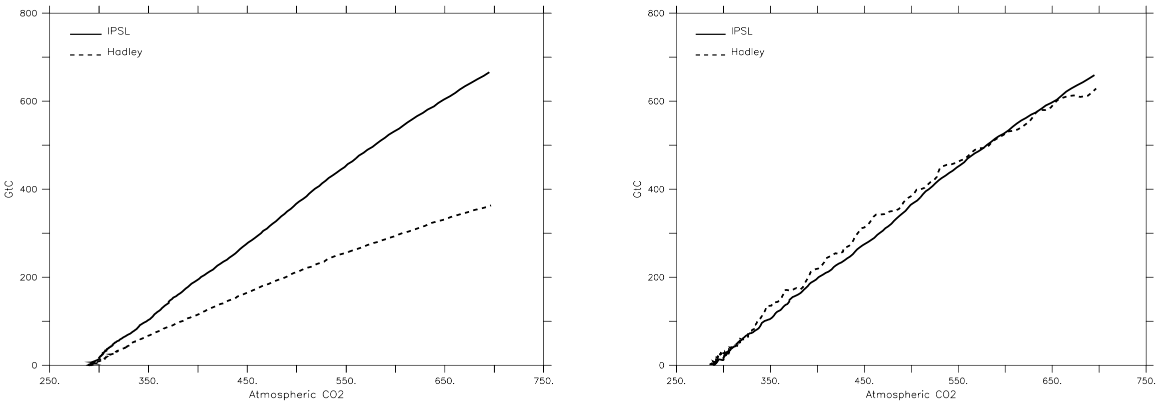

Figure 3. IPSL (solid line) and Hadley (dashed line) carbon cycle models sensitivity to atmospheric CO_2. Figure 3a shows the oceanic uptake as a function of atmospheric CO_2, figure 3b shows the same for the land.

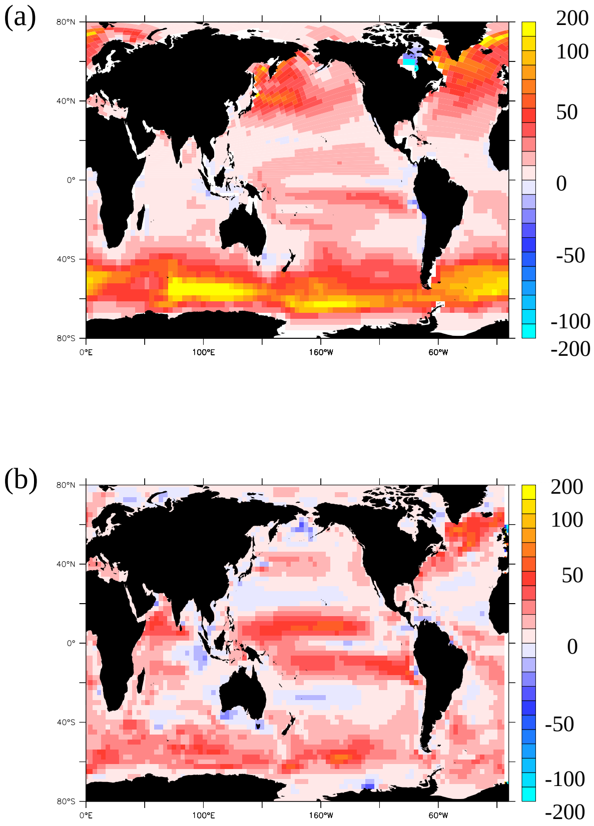

Figure 4. Geochemical oceanic CO_2 uptake (gC/m2/yr) at 700 ppmv for (a) IPSL model, and (b) Hadley model uncoupled runs.

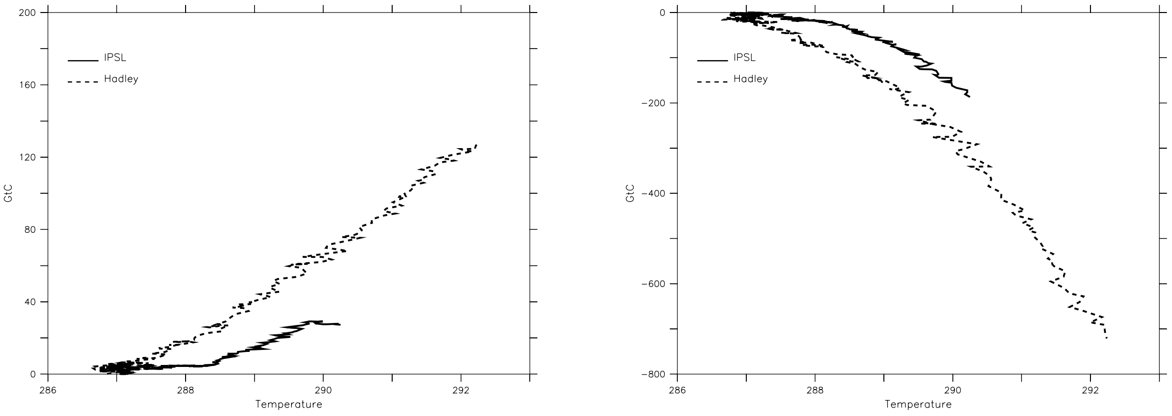

Figure 5. IPSL (solid line) and Hadley (dashed line) carbon cycle models sensitivity to climate. Figure 5a shows the change in oceanic uptake due to change in climate as a function of surface temperature, figure 5b shows the same for the land. As explained in the text, the positive sensitivity seen for the ocean is actually driven by the indirect climate effect through enhanced atmospheric CO_2 (see figure 1).

	α	βab	βao	γab	γao	g	f
Hadley	0.0086	1.66	0.94	-201 (-114.3)	-26.4 (22.5)	0.41	1.69
IPSL	0.0072	1.675	1.7	-89.8 (-45.3)	-36.8 (8.4)	0.166	1.2

Table 1 : Estimate of the climate-carbon cycle feedback for IPSL and Hadley simulations. α is the climate sensitivity to CO_2 (K/ppmv), βab and βao are the land and ocean carbon cycle sensitivity to atmospheric CO_2 (GtC/ppmv), γab and γao are the land and ocean carbon cycle sensitivity to climate change (GtC/K), g is the gain of the feedback, calculated from equation 8, and f is the net feeback factor defined as 1/(1-g). For the calculation of γab and γao, we isolated the direct climate impact on the fluxes from the indirect climate effect through increased atmospheric CO_2 (see equations 7a and 7b). The numbers in parenthesis give the overall effect (direct + indirect).