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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 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 included but assumed to be insensitive to the climate change. The IPSL coupled climate – carbon cycle model simulated a much smaller positive feedback: climate impact on the 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 latter (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 et al., 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 that climate changes reduces the uptake of carbon (e.g., Cao and Woodward, 1998; Cramer et al., 2001; Sarmiento and Le Quéré, 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 account properly for the potentially large feedbacks between these two systems. Such analysis has been performed by two groups from the Hadley Centre, UK (Cox et al., 2000) and from IPSL (Dufresne et al., 2002) in the context of historical and future climate change, using IPCC CO_2 emission scenarios. In this paper we summarise these two studies, highlighting the main mechanisms responsible for the differences between the Hadley Centre and the IPSL results.

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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 Centre 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: sulfate aerosols emissions are ignored, land use change is not accounted for in the land surface model, and nitrogen and other nutrient/toxic depositions on land and ocean are ignored. However, the Hadley model accounts for non-CO_2 greenhouse gases emissions while the IPSL model only accounts for CO_2 emissions. Also, while the land surface scheme of the Hadley model accounts for vegetation dynamics, while the IPSL model does not, vegetation distribution being held at its present-day value.

Each group performed three runs: (a) a control coupled run with no anthropogenic emission, hereafter referred to as the control run; (b) a coupled run with IPCC emissions, leading to increased CO_2 and climate change, hereafter referred to as the coupled run; (c) an uncoupled run with the same IPCC emissions as in (b), but with the climate from the control run, hereafter referred to as the 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

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

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

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

where F_{IPCC} is the IPCC scenario emission of CO_2 (in GtC yr^{-1}), F_{AO}^0, $F_{\text{AO}}^{\text{cou}}$, $F_{\text{AO}}^{\text{unc}}$ (F_{AB}^0, $F_{\text{AB}}^{\text{cou}}$, $F_{\text{AB}}^{\text{unc}}$) are the 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 sulfate 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 present day, producing a CO_2 concentration of 395 ppmv (as opposed to the observed 375 ppmv) and a temperature rise of 1.0 K (as opposed to the observed 0.5 K). This overestimate of historical warming is consistent with the neglect of sulfate 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 sulfate 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 sulfate 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 emission scenarios (Fig. 1). Although the scenarios are identical to the present day, the SRES A2 emissions used by IPSL reach about 29 GtC yr^{-1} by 2100, as opposed to about 20 GtC yr^{-1} 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 and 780 ppmv in the Hadley Centre and IPSL models, respectively. Although the two models simulate a positive

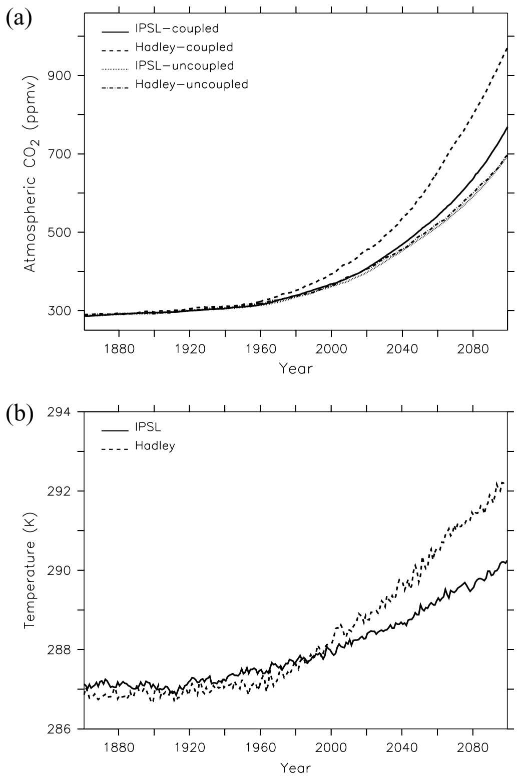

Fig. 1. Calculated atmospheric CO_2 and (b) surface temperature for the IPSL (solid line) and Hadley (dashed line) coupled runs. Atmospheric CO_2 obtained in the Hadley and IPSL uncoupled runs are also shown in (a).

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 in behaviour between the Hadley and the IPSL coupled models. 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:

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

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

with $\Delta F_{\mathrm{AO}} = \beta_{\mathrm{AO}} \Delta CO2 + \gamma_{\mathrm{AO}} \Delta T$ and

$$\Delta F_{\mathrm{AB}} = \beta_{\mathrm{AB}} \Delta CO2 + \gamma_{\mathrm{AB}} \Delta T, \quad (6)$$

ΔT_{ind} being the climate change due to any other forcing than CO_2 (e.g. other greenhouse gases, ozone, aerosols, solar variability etc.). With the definition of eq. (6), one can easily redefine the atmosphere–ocean CO_2 fluxes as:

$$F_{\mathrm{AO}}^{\mathrm{cou}} = F_{\mathrm{AO}}^{0} + \beta_{\mathrm{AO}} \Delta CO2^{\mathrm{cou}} + \gamma_{\mathrm{AO}} \Delta T \text{ and}$$
$$F_{\mathrm{AO}}^{\mathrm{unc}} = F_{\mathrm{AO}}^{0} + \beta_{\mathrm{AO}} \Delta CO2^{\mathrm{unc}} \quad (7a)$$

and similarly for the atmosphere–land fluxes:

$$F_{\mathrm{AB}}^{\mathrm{cou}} = F_{\mathrm{AB}}^{0} + \beta_{\mathrm{AB}} \Delta CO2^{\mathrm{cou}} + \gamma_{\mathrm{AB}} \Delta T \text{ and}$$
$$F_{\mathrm{AB}}^{\mathrm{unc}} = F_{\mathrm{AB}}^{0} + \beta_{\mathrm{AB}} \Delta CO2^{\mathrm{unc}} \quad (7b)$$

One can introduce eq. (6) into eq. (4) to get:

$$\Delta CO2 = \frac{\int_0^t F_{\mathrm{IPCC}}}{1 + \beta_{\mathrm{AO}} + \beta_{\mathrm{AB}}} - \frac{(\gamma_{\mathrm{AO}} + \gamma_{\mathrm{AB}})\Delta T}{1 + \beta_{\mathrm{AO}} + \beta_{\mathrm{AB}}}$$

which, when introduced into eq. (5) gives:

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

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

and $\Delta T_{\mathrm{unc}} = \dfrac{\alpha \int_0^t F_{\mathrm{IPCC}}}{1 + \beta_{\mathrm{AO}} + \beta_{\mathrm{AB}}} + \Delta T_{\mathrm{ind}}.$ (10)

g is the gain of the feedback and ΔT_{unc} is the change in temperature 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).

Similarly, introducing eq. (6) into eq. (5), and then eq. (5) into eq. (4) would give:

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

From eq. (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, or 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

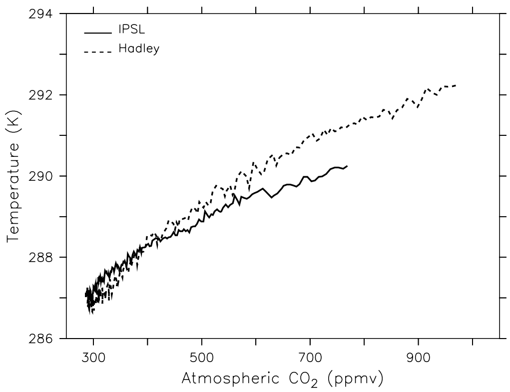

Fig. 2. Climate sensitivity (surface warming as a function of atmospheric CO_2) for IPSL (solid line) and Hadley (dashed line) coupled models.

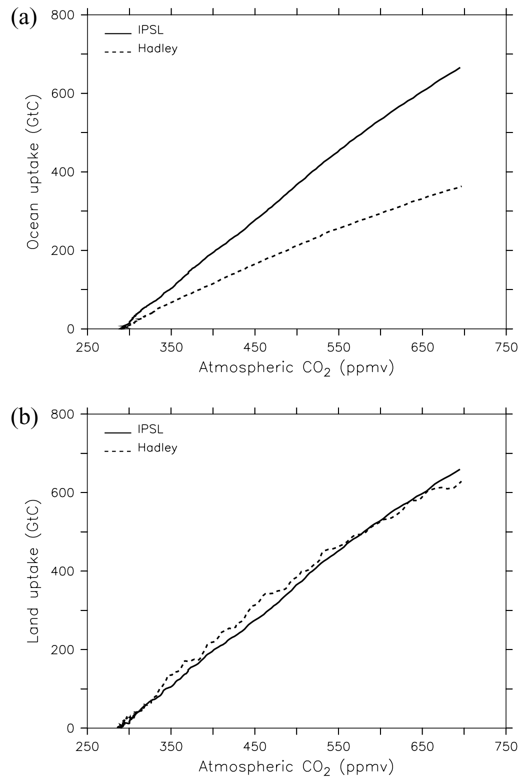

Fig. 3. IPSL (solid line) and Hadley (dashed line) carbon cycle models sensitivity to atmospheric CO_2: (a) the oceanic uptake as a function of atmospheric CO_2; (b) the same for the land.

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 analysed 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 does the IPSL (Fig. 2). However, this can easily be explained by the difference in the forcing applied to the models. Although neither of the models accounts for change in aerosol emissions, the Hadley model accounts for both CO_2 and non-CO_2 emissions (CH_4, N_2O, etc.) 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 were expressed as a function of radiative forcing, the two models would give close results. However, for the sensitivity analysis we do here, this is not a crucial issue, as the carbon cycle sensitivities to climate change that we will calculate are normalised quantities (GtC $^{\circ}C^{-1}$).

4.2. Carbon cycle sensitivity to CO_2 alone

Here we analyse 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 Fig. 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 has 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 (β_{AO}) than the IPSL model. At 700 ppmv, the Hadley geochemical oceanic uptake amounts to 4 GtC yr^{-1}, while the IPSL uptake reaches 8 GtC yr^{-1}. This 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 (Fig. 4) one clearly sees that the CO_2 uptake

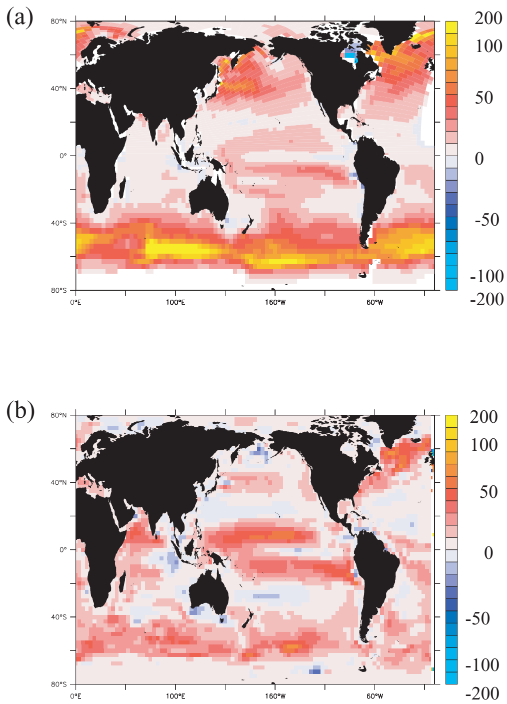

Fig. 4. Geochemical oceanic CO_2 uptake (gC m^{-2} yr^{-1}) at 700 ppmv for (a) the IPSL model and (b) the Hadley model uncoupled runs.

in the Southern ocean is about twice as large in the IPSL run than in the Hadley run. Higher oceanic convection at these latitudes explains 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 the Southern Ocean is one of the regions where differences amongst models are the largest (Dutay et al., 2001; Orr et al., 2001). Comparisons with observations indicated that IPSL slightly overestimates tracer penetration in these regions. The southern ocean regions play a crucial role in the present-day CO_2 budget, but the magnitude of the CO_2 uptake in these regions is highly debated. Recent observations obtained in the southern Indian Ocean (OISO cruises in January and August 2000) indicate significant seasonal variations of the air–sea CO_2 flux and suggest that the ocean sink is small during the austral winter (N. Metzl, personal communication). Also, atmospheric (Gurney et al., 2002) and recent oceanic inversions (N. Gruber, personal communication) suggest a southern ocean sink that is lower than the estimates from Takahashi et al., (2002). 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 alone

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 (Fig. 5). However, these two

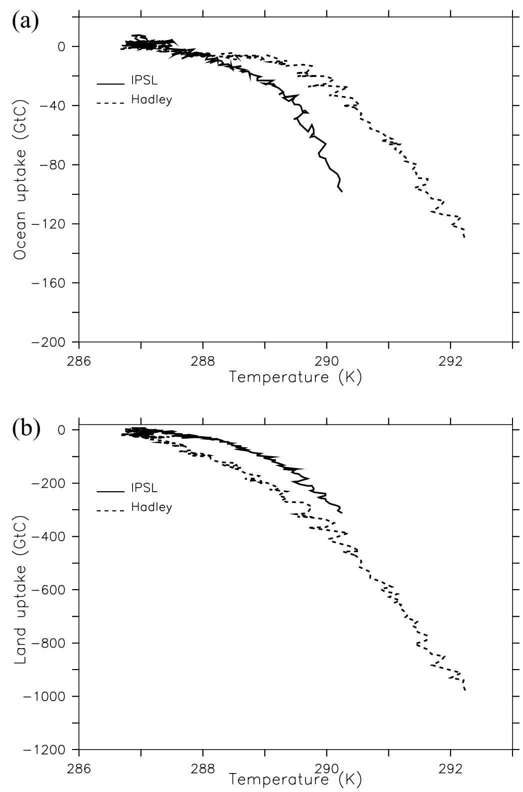

Fig. 5. Sensitivity of the IPSL (solid line) and Hadley (dashed line) carbon cycle models to climate change alone. (a) The change in oceanic uptake due to change in climate as a function of surface temperature; (b) the same for the land. As explained in the text, the fluxes have been corrected for the indirect climate effect through enhanced atmospheric CO_2 (see Fig. 1).

runs also differ as the atmospheric CO_2 level is higher in the coupled runs. Therefore, to calculate the carbon cycle sensitivity to climate change alone, we first need to isolate the differences in CO_2 uptake induced by the climate change from those induced by the different atmospheric CO_2levels. To do so, we use the carbon cycle sensitivities to atmospheric CO_2 (β_{AO} and β_{AB}) calculated above to calculate what would be the ocean (land) uptake in the coupled run if the atmospheric CO_2 were fixed at the level of the uncoupled run. Mathematically we estimate this corrected flux as follows:

$$F_{AO}^{cor} = F_{AO}^{cou} - \beta_{AO}\left(CO_2^{cou} - CO_2^{unc}\right),$$

and similarly for the land CO_2 fluxes. Figure 5 shows these corrected fluxes plotted against the temperature changes for both the Hadley and IPSL models.

The land carbon component of the Hadley model shows a much more negative γ_{AB}, the carbon flux sensitivity to climate change alone, than the IPSL model. This feature was already mentioned by Dufresne et al. (2001). This is mainly due to difference in the vegetation and soil carbon dynamics. In the uncoupled run, the Hadley model gives a large carbon allocation to the soil compartment, while IPSL mainly stores carbon in living vegetation. The warming that occurs in the coupled run induces a larger and widespread soil carbon release in the Hadley framework, a pattern mainly confined in the tropics in the IPSL simulation. There are few 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 an enhanced growth rate under elevated CO_2 (25% increase for a 200 ppmv increase in atmospheric CO_2) (DeLucia et al., 1999) but still a 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 negative γ_{AO}, the sensitivity of the ocean carbon uptake to climate change alone. The γ_{AO} of IPSL is more negative than that of Hadley. This feature is consistent with the fact that the Hadley ocean uptake sensitivity to CO_2 is also lower than that of IPSL (see section above). Climate change induces a stabilisation of the water column, which shuts off convection and reduces the slopes of the density surfaces. Most of this occurs in the Southern Ocean. Since Hadley has a much lower uptake (i.e. much less convection) in these regions than IPSL, the first model is affected much less than the latter by the stabilisation of the water column.

4.4. Analytical estimate of the feedback

Using eq. (9), we can now estimate the gain of the climate – carbon cycle feedback for both the Hadley and IPSL simulations. From Figs. 2, 3 and 5, we can derive the terms α, β_{AB}, β_{AO}, γ_{AB} and γ_{AO} and then calculate the terms g and f for both models (Table 1). 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. The values are very close to the overall feedback factor that can be derived from Fig. 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, i.e., an amplification of 1.19. For the Hadley simulations, the values are 692 vs. 413 ppmv, i.e. an amplification of 1.675.

The remarkably close agreement between our analytical estimate and the observed estimate (from Fig. 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-order 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

Table 1. *Estimate of the climate – carbon cycle feedback for IPSL and Hadley simulations*[a]

Model	α	β_{AB}	β_{AO}	γ_{AB}	γ_{AO}	g	f
Hadley	0.0086	1.66	0.94	−201	−26.4	0.41	1.69
IPSL	0.0072	1.675	1.7	−89.8	−36.8	0.166	1.2

[a] α is the climate sensitivity to CO_2 (K ppmv^{-1}), β_{AB} and β_{AO} are the land and ocean carbon cycle sensitivity to atmospheric CO_2 (GtC ppmv^{-1}), γ_{AB} and γ_{AO} are the land and ocean carbon cycle sensitivity to climate change (GtC K^{-1}), g is the gain of the feedback, calculated from eq. (8), and f is the net feedback factor defined as $1/(1-g)$. For the calculation of γ_{AB} and γ_{AO}, we isolated the direct climate impact on the fluxes from the indirect climate effect through increased atmospheric CO_2 (see text for detail).

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 β_{AO} value from IPSL in the Hadley framework would reduce 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, i.e. using the β_{AO} value from Hadley, would increase the IPSL gain to 0.19, which translates into an atmospheric CO_2 concentration of 795 ppmv (i.e. only 15 ppmv higher than in the coupled IPSL simulation).

Doing a similar calculation with the land component gives more dramatic results. Indeed using the land carbon cycle sensitivity to climate, γ_{AB}, of IPSL in the Hadley framework would lower the gain to 0.21, translating into an atmospheric concentration of 810 ppmv (i.e. 170 ppmv less than in the Hadley coupled simulation and only 30 ppmv higher than the value obtained in the IPSL coupled runs). The IPSL model with the Hadley γ_{AB} 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 thus clear that, although the strength of the oceanic geochemical uptake is a non-negligible term, the dominant factor is the climate sensitivity of the land carbon model. A calculation of the total derivative of the gain equation [eq. (9)] given in the Appendix confirms these results, that the main term driving the difference between the Hadley and the IPSL runs is γ_{AB}.

5. Conclusions

In this study we compared the response of two climate models coupled to carbon cycle models and forced by CO_2 emission scenarios for the 1860–2100 period. Both the 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 two 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: (i) the Hadley model has a more negative land carbon sensitivity to climate, mainly because of faster cycling of carbon through the living biomass; (ii) 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. This translates into 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.

6. Acknowledgements

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Appendix

The total derivative of g is:

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

Using eq. (8) we can calculate the partial derivatives:

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

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

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

For clarity, here we grouped 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 [eqs. (A1)–(A3)] for IPSL, amounting respectively, to 23 ppmv K^{-1}, $1.3e^{-3}$ K GtC^{-1} and $3.e^{-2}$ ppmv GtC^{-1}. 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 sensitivity of g to α and γ is slightly larger than the sensitivity of g 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 that are less 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.

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