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The African contribution to the global climate-carbon cycle feedback of the 21st century

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Abstract

Future climate change will have impact on global and regional terrestrial carbon balances. The fate of African tropical forests over the 21st century has been investigated through global coupled climate carbon cycle model simulations. Under the SRES-A2 socio-economic CO_2 emission scenario of the IPCC, and using the Institut Pierre Simon Laplace coupled ocean-terrestrial carbon cycle and climate model, IPSL-CM4-LOOP, we found that the warming over African ecosystems induces a reduction of net ecosystem productivity, making a 20% contribution to the global climate-carbon cycle positive feedback. However, the African rainforest ecosystem alone makes only a negligible contribution to the overall feedback, much smaller than the one arising from the Amazon forest. This is first because of the two times smaller area of forest in Africa, but also because of the relatively lower local land carbon cycle sensitivity to climate change. This beneficial role of African forests in mitigating future climate change should be taken into account when designing forest conservation policy.

1 Introduction

Coupled climate carbon cycle studies highlighted the vulnerability of the continental biosphere to human induced climate change (Cox et al., 2000; Dufresne et al., 2002). In particular tropical forest ecosystems may play a key role in future changes in global carbon balance. These ecosystems represent the largest reservoir of living biomass. The balance between carbon uptake through photosynthesis and release from decomposition of organic matter is sensitive to changes in climate regime, such as increased aridity. Climate variability and rising CO_2 have also an impact on tropical forest biomass growth rates and mortality (Clark et al., 2003), and on CO_2 emissions related to fire disturbances (Nepstad et al., 2004). There is a consensus among the coupled climate carbon cycle models to simulate a decrease of terrestrial carbon uptake in the tropics under future climate change (Friedlingstein et al., 2006, hereafter F06). This decreased tropical land uptake is a dominant contributor to the positive carbon cycle – climate feedbacks found in coupled models. Its causes have to be found in a combination of reduced photosynthesis due to a warming, generally combined with an increase in soil aridity, as well as an increase in soil oxidation, due to the warming. Some models also simulate a decrease of forest density, and a gradual replacement by savannah type ecosystems. On shorter time scales, such as the interannual variability, recent studies also highlighted the dominant role of tropical ecosystem in the control of atmospheric CO_2 growth rate (e.g. Rodenbeck et al., 2003; Peylin et al., 2005; Baker et al., 2006). The El Niño/Southern Oscillation (ENSO) climate variability induces large excursions in photosynthesis and/or decomposition and fires (Page et al., 2002) leading to anomalous CO_2 release from tropical ecosystems during El Nino events, and conversely to anomalous uptake during the cooler and wetter La Niña episodes. However, the effect of drought in decreasing C uptake as simulated by all global models, was recently challenged by field measurements showing locally more C uptake by tropical forests during the dry periods (Saleska et al., 2007; Bonal et al., 2008). However, so far, within the tropical forest, most of the focus has been given to the Amazon basin (Cox, et al., 2004; Betts et al., 2004; Huntingford et al., 2004). For example, the fate of the Amazon forest has been largely investigated, as this ecosystem show a very strong positive feedback, i.e., carbon release, through its dieback in the Hadley Centre future climate-carbon simulations (Cox et al., 2000, 2004). Also the Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) program (http://lba.inpa.gov.br/lba) provided ecosystem and atmospheric data that were used by models in order to gain process understanding of the Amazon forest. Oppositely, very few studies focused on the African tropical forest and savannas biomes, their role in the global present carbon cycle and its vulnerability to future climate change.

2 Methodology

In a companion paper (Ciais et al., 2008), we used the ORCHIDEE global land ecosystem model (Krinner et al., 2005) forced by the observed evolution of the climate of the 20th century to investigate the present and historical African carbon balance. Here, we used the same land surface model, ORCHIDEE, but embedded within the Atmosphere Ocean General circulation model of IPSL in order to simulate the past and future evolution of the climate and carbon cycle. The IPSL-CM4-LOOP model couples the ocean-atmosphere general circulation model IPSL-CM4 (Dufresne et al., 2007) and the land and ocean carbon cycle models, ORCHIDEE (Krinner et al., 2005) and PISCES (Aumont and Bopp, 2006).

Following the coupled climate carbon cycle model intercomparison project (C4MIP) protocol described in F06, we performed two climate-carbon coupled simulations (UNC and COU) over the 1860–2100 period. In both experiments, CO_2 emissions are prescribed from historical data for 1860–2000 (Marland et al., 2005; Houghton and Hackler, 2002) and from the SRES-A2 scenario for the 21st century (Nakićenović, et al., 2000). The other greenhouse gas concentrations are set to pre-industrial values. COU and UNC differ because in UNC, CO_2 is treated as a non-radiatively active gas, so that the carbon cycle experiences no CO_2-induced climate change. The difference between these two runs defines the climate carbon cycle feedback.

3 Results

The global results of the IPSL-CM4-LOOP model have been described in previous papers (F06, Cadule et al., 2008). Here we will shortly summarize the main performance of the model. The COU simulation leads to a global surface warming of 3.7 K by 2100 and an atmospheric CO_2 concentration of 807 ppm. The UNC simulation, with no climate change, leads to a CO_2 concentration of 776 ppm, The difference, i.e. 31 ppm, is due to a decrease of both land and ocean carbon uptake under future climate conditions. The cumulated land sinks decreases by 80 GtC while the ocean sinks decrease by 65 GtC between 1901 and 2100.

When compared to the other C4MIP models, IPSL-CM4-LOOP has a lower than the average climate carbon cycle feedback. The CO_2 amplification, 31 ppm, translates in a gain of 6%, where the C4MIP models show an average amplification of 85 ppm, that is, an average gain is 15%. This low gain cannot be explained by the climate sensitivity of the climate model as it is on the higher end of the C4MIP models. It is rather a direct result of the low sensitivity of the land carbon cycle to the climate change (called γ_L in F06). We defined γ_L as the difference in cumulated NEP in COU and UNC (corrected by the effect of atmospheric CO_2 difference between the two simulations), normalized by the surface temperature change between COU and UNC (see F06 and Friedlingstein et al., 2003 for details). In other words, γ_L describes the sensitivity of the land carbon cycle to warming. In IPSL-CM4-LOOP, γ_L amounts to $-20\,\mathrm{GtC\,K^{-1}}$, where the C4MIP models average is $-80\,\mathrm{GtC\,K^{-1}}$. ORCHIDEE simulates a climate induced reduction of Net Ecosystem Productivity (NEP) in the tropics but largely balanced by an increased NEP in mid and high latitudes ecosystems. This positive NEP response is partly due to a cold bias in the UNC climate of the model in these regions.

Over Africa, the model simulates a regional warming by the end of the 21st century. This warming amounts to 3 K in the Congo basin, but reaches 6 K in South Africa and in northern Sahel (Fig. 1). The associated change in precipitation is an increase in precipitation around the equator (up to $300\,\mathrm{mm\,yr^{-1}}$; +20%) and a reduction in precipitation outside of the tropical belt (up to $100\,\mathrm{mm\,yr^{-1}}$) (Fig. 1). The regions with more warming also experience drying, while regions (Central Africa) which warm moderately experience wetter conditions in the future. These results are consistent with the ones obtained by the IPCC 4th Assessment Report climate models for the SRES-A2 scenario (see Fig. 11.2 of IPCC Working Group 1, 4th Assessment Report, Christensen et al., 2007). This climate change pattern is rather similar to the conditions of a permanent El Niño episode over the African continent (see Ciais et al., 2008).

When looking at the carbon cycle, the Gross Primary Productivity (GPP) of the COU coupled run increases everywhere across Africa, the largest increase being, as could be expected, in the already most productive regions of the African rainforest (Fig. 2). Overall GPP increases from 26 GtC yr^{-1} at pre-industrial up to 40 GtC yr^{-1} by 2100. Across the tropical rainforest ecosystem, this increase is a combination of both GPP enhancement by atmospheric CO_2 (fertilization) and by climate change. Indeed, the difference of GPP between the coupled and the uncoupled runs is positive over Africa (+2 GtC yr^{-1}) (Fig. 3). The climate induced increase in GPP represents up to 20% of the total GPP increase. We note that at the fringes of the tropical forest biome, for savannah type ecosystems as well as over Southern Africa, the model simulates a decrease of GPP induced by the future climatic conditions.

Despite that climate and CO_2-induced stimulation of GPP over Africa and in particular over the African rainforest, NEP is reduced when climate change is taken into account (Fig. 3). The total African NEP cumulated over 1860–2100 amounts to 76 GtC in the COU run while it reaches 102 GtC in UNC (Fig. 4). The apparent paradox between enhanced GPP and reduced uptake comes from the total respiration response to climate change. Autotrophic and especially heterotrophic respiration shows an important increase due to the regional warming which is larger than the productivity response (Fig. 3). One can see from the carbon balance that living biomass does increase under future climate (i.e. Net Primary Productivity increases in excess of litterfall) but soil carbon is largely reduced (i.e. heterotrophic respiration increases in excess of litter input) (Fig. 3). Altogether, the loss of carbon from soil dominates. By 2100, a carbon loss of 26 GtC occurs in COU relative to UNC. Similarly, cumulated NEP is reduced by 5 GtC for the African rainforest alone.

A cumulated release of 26 GtC to the atmosphere would translate into an increase in concentration of about 6 ppmv, assuming an airborne fraction of 0.5. The African carbon response to climate change represents then about 20% of the global feedback of the IPSL-CM4-LOOP model (31 ppm). The contribution from the African tropical forest alone is only 5 GtC, which translates into about 1 ppm, i.e. as very small contribution to the global feedback. However, we note that the relative climate-carbon feedbacks are not simply additive as some regions, such as the high latitudes of the northern hemisphere have a negative contribution to the overall positive feedback.

4 Discussion

Doing a similar calculation of the carbon loss from the Amazon forest shows that in the IPSL-CM4-LOOPmodel, the Amazon forest gives a much larger contribution, 29 GtC reduction of 1860–2100 cumulated NEP in COU relative to UNC (Fig. 4). Part of this larger contribution comes from the area of the domain considered. Indeed, the area of the Amazon basin is twice as large as the African rainforest basin. Also, in the Amazon, the carbon loss is largely driven by the reduction of GPP due to the increased aridity. A climatic pattern sometimes referred as a "perpetual El Niño". In Africa, during such "perpetual El Niño" the precipitation pattern is drastically different with an enhancement of precipitation over tropical rain forest and a reduction over already more arid regions (north equatorial and southern African savannas). In the African rainforest, as explained above, the carbon loss only comes then from an enhanced respiration due to the warming trend.

In order to compare the NEP response of regions with different surface area, we define here a local land carbon cycle sensitivity to climate change (in $\mathrm{gC\,m^{-2}\,K^{-1}}$)$\bar{\gamma}_L$, which is the standard γ_L divided by the area of the considered domain. For the African rainforest, $\bar{\gamma}_L$ amounts to $-483\,\mathrm{gC\,m^{-2}\,K^{-1}}$, a value not that different from the one obtained for the Amazon forest ($-653\,\mathrm{gC\,m^{-2}\,K^{-1}}$).

To explore the robustness of our results to the simulation of the climate, we made use of the IMOGEN simple climate model analogue (Huntingford and Cox 2000; Huntingford et al., 2004). IMOGEN adopts a pattern scaling approach, using the climate patterns from the Hadley Centre model (HadCM3-LC) (Cox et al., 2000). The IMOGEN climate analogue model has been coupled to several dynamic vegetation models, including ORCHIDEE, in order to evaluate their climate-carbon cycle feedback (Sitch et al., 2008). Here we use the output of an IMOGEN-ORCHIDEE simulation, forced by historical and SRES-A2 emissions of CO_2 as in the IPSL-CM4-LOOP coupled simulation described above.

The HadCM3-LC climate change patterns as reproduced by IMOGEN (Fig. 5) are dramatically different from the ones obtained with the IPSL-CM4-LOOP model (Fig. 1) IMOGEN shows a strong dipole between the precipitations changes over the Amazon vs. the African rainforest. HadCM3-LC simulates a very strong precipitation reduction over the Amazon rainforest, a pattern not produced by IPSL-CM4-LOOP, while it does simulate, as in IPSL-CM4-LOOP, an increase in precipitation over Eastern tropical Africa. Also, the warming over the Amazon is almost a factor of two larger than over the African rainforest in the HadCM3-LC model, whereas the IPSL-CM4-LOOP simulates warming of similar amplitudes for the two rainforest basins. Over the African rainforest, the Hadley and IPSL climate models simulate then comparable climate change patterns, and hence similar terrestrial response with ORCHIDEE. However, we note that the IMOGEN-ORCHIDEE coupled simulations give a larger than IPSL-CM4-LOOP climate induced reduction in GPP and NEP over the western and southern part of the African continent, essentially driven by the precipitation reduction in these regions (Fig. 6). Over the Amazon, the two models have drastically different responses: the Hadley climate induces a carbon loss a factor of 5 larger than the one simulated by the IPSL-CM4-LOOP model. This is essentially because of the very different climate projections in the Amazon between Hadley and IPSL. Also, $\bar{\gamma}_L$, the local land carbon uptake sensitivity to climate change is almost a factor of two larger over the Amazon than over the African rainforest under the Hadley centre future climate (Table 1). Oppositely, for the IPSL climate, Amazon and Africa have more similar γ_L. As a result, the coupled IMOGEN-ORCHIDEE model simulates a much larger NEP reduction in the Amazon (149 GtC) than in the African rainforest (31 GtC), just like in the standard HadCM3-LC model simulations (Cox et al., 2000) (Fig. 7).

5 Conclusions

Tropical ecosystems will be put at risk over the coming century, due to climate change, but also due to the direct anthropogenic pressure, through deforestation (not accounted for in this study). In the coupled carbon climate simulations that we analyzed, the 21st century climate change leads to a reduction of carbon stocks in both the African and South-American rainforests. Each of them contributes then significantly to the positive global climate-carbon cycle feedback. Altogether, more than 50% of the feedback comes from Africa and South America in the IPSL-CM4-LOOP simulations. However, when looking at the tropical rain forest ecosystem alone, the contribution from Africa is much lower than the one from South America. Finally, we found that there is still a large uncertainty in the feedback of African vs. Amazon rainforests due to the simulated climate change at the regional scale and its impact on the carbon fluxes. This is true for the African continent, but especially over the Amazon basin, where the Hadley Centre climate model simulates a much larger climate change (warming and drying) and hence a five times larger carbon loss than the IPSL climate model.

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Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
|◀ | ▶|
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

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Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

◀◀ | ▶▶

◀ | ▶

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Table 1. Change in Net Ecosystem Productivity and associated carbon cycle sensitivity over Africa, African rainforest and Amazon tropical forest. Results are given for the IPSL-CM4-LOOP simulation and for the IMOGEN simulations of ORCHIDEE using the HadCM3-LC climate change patterns.

	Cumulated NEP Coupled run	Cumulated NEP Uncoupled run	Climate induced NEP reduction	Local Gamma ($gC\,m^{-2}\,K^{-1}$)
	(GtC)	(GtC)	(GtC)	
LOOP/IMOGEN Africa	76/105	102/192	26/87	−265/−479
LOOP/IMOGEN African rainforest	65/59	70/90	5/31	−483/−1098
LOOP/IMOGEN Amazon rainforest	59/4	78/153	29/149	−653/−1813

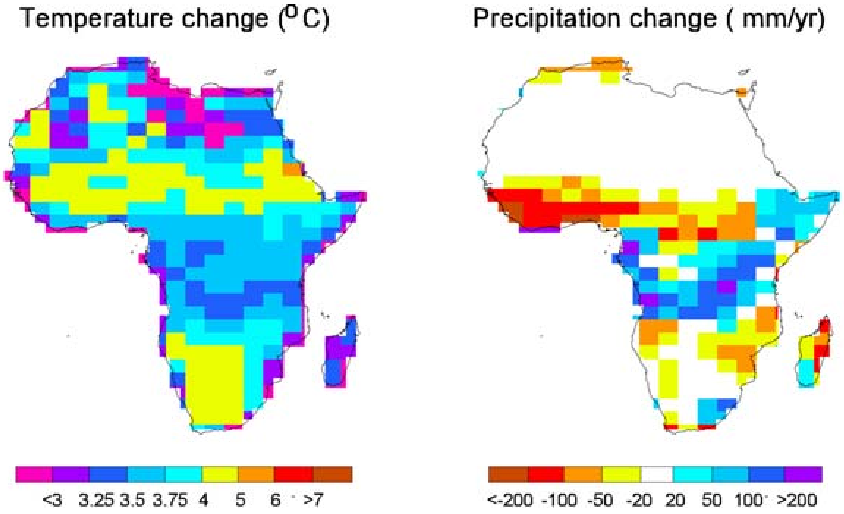

Fig. 1. Climate change (2090s relative to 1860s) simulated with the IPSL-CM4-LOOP coupled model over Africa. Left panel is for surface temperature change (K), right panel is for precipitation changes (mm yr^{-1}).

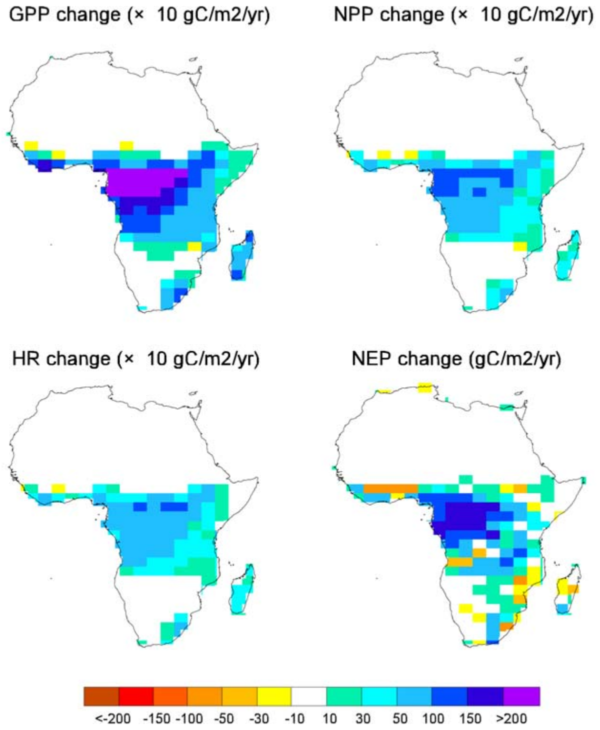

Fig. 2. Carbon fluxes change (2090s relative to 1860s) from IPSL-CM4-LOOP coupled simulation (COU) over Africa. Top left panel is for Gross Primary Productivity, top right panel is for Net Primary productivity, bottom left panel is for Heterotrophic Respiration, and bottom right is for Net Ecosystem Productivity (all in gC m^{-2} yr^{-1}). Note that first three quantities have to be multiplied by 10.

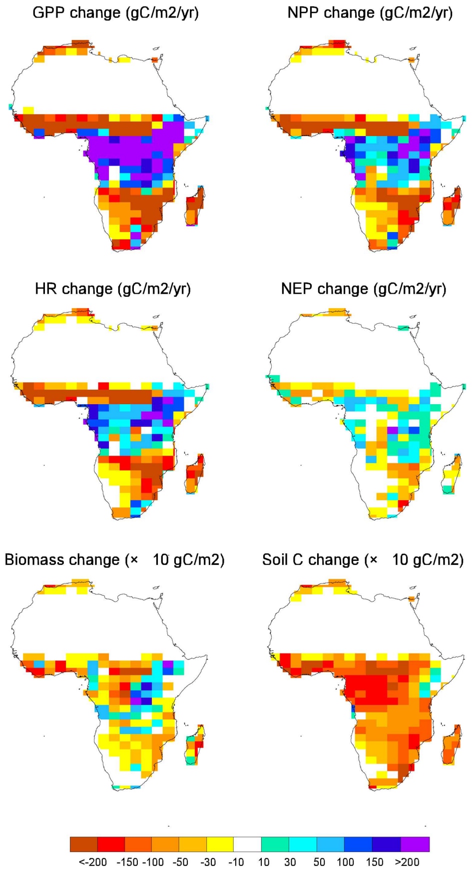

Fig. 3. Climate induced change in carbon fluxes and stocks (2090s) from IPSL-CM4-LOOP coupled (COU) relative to uncoupled (UNC) simulation over Africa. Top left panel is for Gross Primary Productivity, top right panel is for Net Primary productivity, middle left panel is for Heterotrophic Respiration, and middle right is for Net Ecosystem Productivity (all in gC m^{-2}yr^{-1}). Bottom left panel is for carbon stored in biomass, and bottom right is for carbon stored in litter and soil (both in gC m^{-2}). Note that last two quantities have to be multiplied by 10.

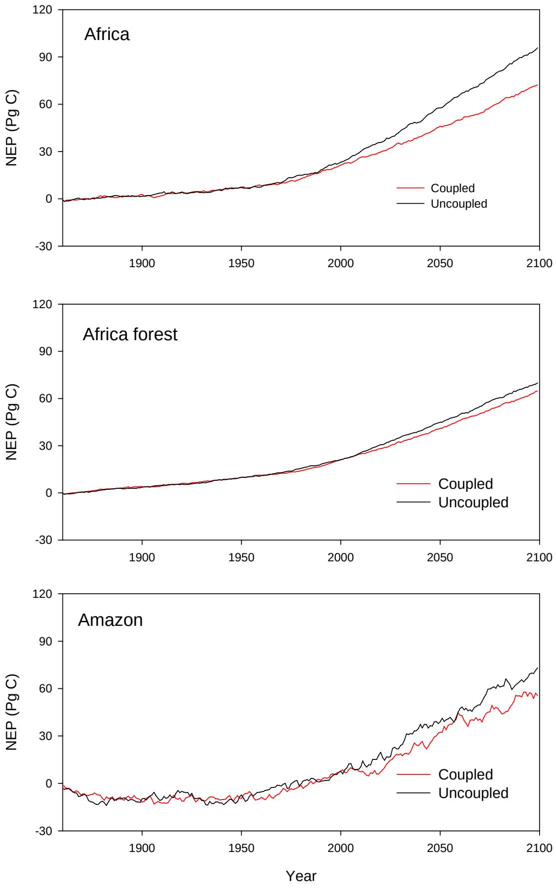

Fig. 4. Time evolution of cumulated change in NEP from IPSL-CM4-LOOP coupled (in black) and uncoupled (in red) simulations over the Africa continent (top panel), the African rainforest (middle panel) and the Amazon basin (lower panel). Units are GtC.

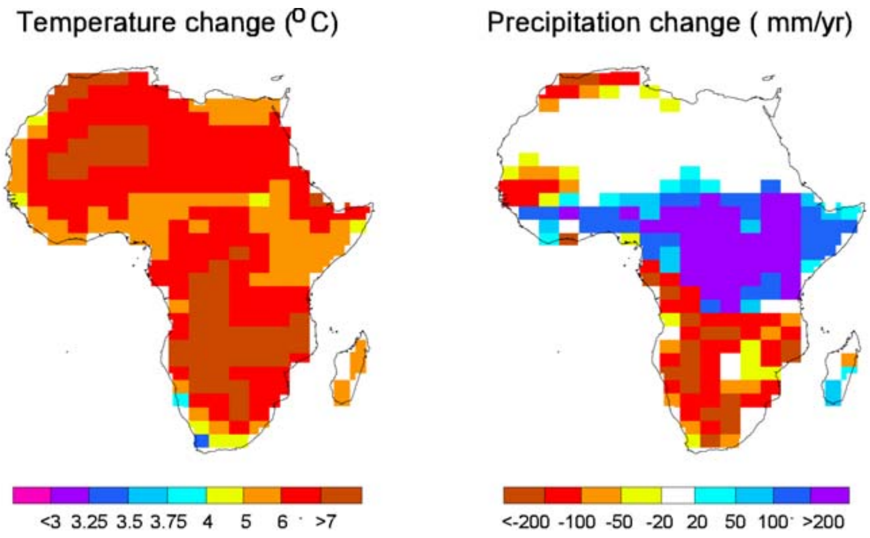

Fig. 5. Climate change (2090s relative to 1860s) simulated with the IMOGEN model, using the HadCM3-LC patterns. As in Fig. 1, left panel is for surface temperature change (K), right panel is for precipitation changes (mm yr^{-1}).

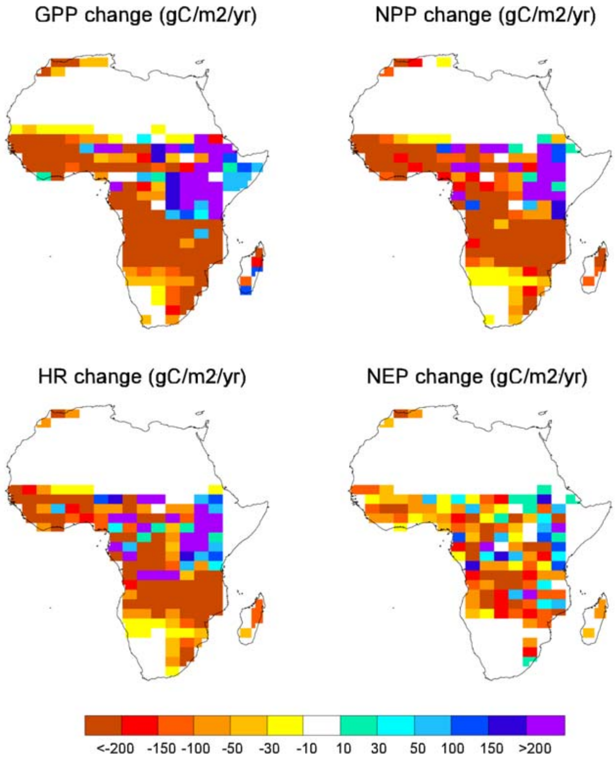

Fig. 6. Climate induced change in carbon fluxes and stocks (2090s) from the simulations with the IMOGEN model coupled to ORCHIDEE over Africa. Top left panel is for Gross Primary Productivity, top right panel is for Net Primary productivity, middle left panel is for Heterotrophic Respiration, and middle right is for Net Ecosystem Productivity (all in gC m^{-2} yr^{-1}).

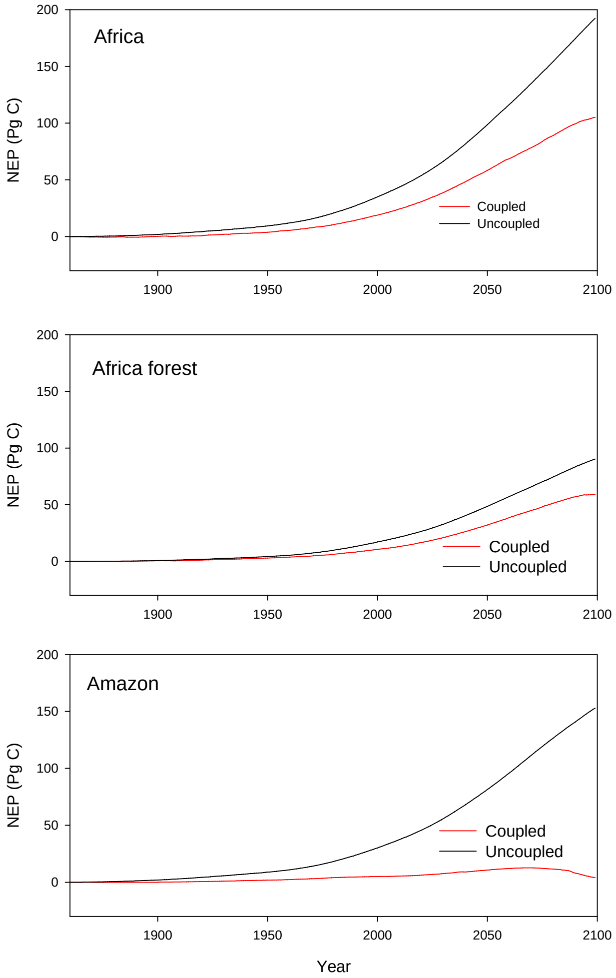

Fig. 7. As Fig. 4, but for the IMOGEN-ORCHIDEE simulations.