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Quantifying the impact of future land-use changes against increases in GHG concentrations

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The impact on atmospheric climate of future land-use changes relative to the increase in greenhouse gas (GHG) concentrations is assessed in time-slice simulations with the ARPEGE-Climat atmospheric general circulation model (AGCM). Future land cover maps are provided by the IMAGE2.2 integrated model, developed by RIVM. We show that the relative impact of vegetation change to GHG concentration increase is of the order of 10% for a B2 scenario, and can reach 30% over localized tropical regions.

1. Introduction

Several studies [*Zhao and Pitman* [2002b], *Chase et al.* [2000], *Bounoua et al.* [2002]] have shown that past changes in land cover, especially changes in land use, could have had an impact on climate. These studies have mainly focused on the difference between simulated climate when using natural potential land cover map instead of present land cover. Such studies have thus quantified the impact of past land use changes on climate. The vegetation changes that occur in those experiments are mainly a deforestation of the mid-latitudes. It is also of interest to study what will be the impact of future land use changes on climate. For the future, changes are expected to occur mainly in the tropics (deforestation), but there could also be some afforestation in the mid-latitudes. To our knowledge, the impact of future land cover conversions on climate has been first investigated by *DeFries et al.* [2002] who have shown that in the tropics, it could have a larger effect than that expected from the inter-annual variability of vegetation cover. However, in their study, *DeFries et al.* [2002] kept GHGs at the present level and did not investigate the impact of changing land cover on a GHGs concentration enhanced atmosphere. Here, we attempt to quantify the relative impact of land cover change compared to GHGs concentration increase, and to determine whether the impact of vegetation conversion is dependent on the atmospheric climate.

2. Experimental design

To simulate future land-cover maps, we used the IMAGE integrated impact model developed at RIVM [*Alcamo et al.* [1998]] as was used by *DeFries et al.* [2002] and *Feddema et al.* [2005]. This model computes the evolution of land-use and natural land cover on a 0.5° resolution grid. The changes in natural land cover and

land use are both calculated according to climate change and CO₂ increase. The land-use changes also regionally depend on demographic projections, improvement in agricultural practices and take into account the fertilization effect of CO₂. IMAGE land cover projections indicate that future land use changes will mainly occur in the tropics and will be regionally dependent on demographic projections, which themselves depend on the economic scenario. For the present study, we have used results from the scenario B2 for which changes in land cover are important, particularly in the tropics, whereas GHGs concentrations increase is moderate (Figure 1). In such a scenario, the ratio of land-use impacts relative to GHGs impacts is thus enhanced.

We used the atmospheric GCM ARPEGE-Climat from CNRM (version 3) [Déqué [1999]] to assess the impact of a future realistic land cover change on atmospheric climate. To compare this impact with the impact of GHGs concentrations increase, we performed a set of 4 simulations:

1. **CTL**: a control simulation with the land cover map for 1980 (Figure 1), GHGs concentrations for 1980 ($[CO_2] = 337ppm$) and monthly mean climatological SSTs [Smith *et al.* [1996]] for the period 1970-1989.

2. **LU2050**: a simulation with the land-cover map for 2050 (Figure 1) but with the same GHGs and SSTs as CTL.

3. **GLU2050**: a simulation with the land-cover map for 2050 and GHGs concentrations for 2050 according to scenario B2 ($[CO_2] = 478ppm$). SSTs are evaluated from a transient scenario simulation previously performed with the same atmospheric model coupled to the OPA ocean GCM: we calculated mean anomalies over the period 2040-2059 compared to the period 1970-1989 and added them to the climatological SSTs used in experiments CTL and LU2050.

4. **GCTL**: a simulation with the land-cover map for 1980 and GHGs and SSTs for 2050 as in GLU2050.

This ensemble of simulations allows for both an independent comparison of the impacts of land-use change and GHGs increase and an evaluation of the linearity of the response to these changes. Following a 3-year spin-up period, each simulation is run for over 30 years. As the SST forcing is identical every year, we can consider that each simulated year is statistically independent from the others.

To compute moisture and energy fluxes over continental surfaces, the ARPEGE-Climat model includes the ISBA land surface scheme. In this study, the atmospheric model is used in a configuration with 31 levels on the vertical and a 2.8° horizontal resolution. All ISBA vegetation parameters (LAI, vegetation fraction, roughness length, albedo, minimum stomatal resistance, rooting depth, emissivity and thermal coefficient) are affected by land cover changes.

3. Linearity of the response to land-use changes given a different control climate.

As a result of only the change in land-cover, near surface temperatures increase or decrease depending on the region (Figure 2a). There is a warming over mid-latitudes in regions where there is an afforestation during the 21st century. This is mainly due to the reduction of the albedo and to a positive feedback induced by the snow masking effect of forests in winter. In the tropics, the im-

pact is positive or negative depending on the vegetation transition which occurred, as previously pointed out by *Bounoua et al.* [2002]. When crops replace forests (this is the case over equatorial Africa, and southern Asia), there is a large reduction of the thermal inertia of vegetation and the model simulates a large decrease in minimum temperature over the whole annual cycle. There is also a large increase in maximum temperature during the dry season due to the reduction in rooting depth that limits evaporation. However, the net effect of reducing minimum temperature and increasing maximum temperature is a reduction in annual mean temperature when deforesting. This is a characteristic behavior of the ISBA model, that is described in detail in *Voldoire and Royer* [2004]. On the contrary, when crops replace savanna or scrubs, we observe a warming. One could expect that it is due to a decrease in evaporation. However, if transpiration is actually reduced, this is counterbalanced in ISBA by an increase in evaporation from bare soil (due to the increased fraction of bare soil and because rooting depth is not greatly reduced when replacing savanna with crops). In this case, the warming is spatially very well correlated with the change in emissivity that reduces the upward long-wave flux. The changes in mean near-surface temperature over Africa are quite opposite to those simulated in *DeFries et al.* [2002]. This emphasizes the need to repeat such experiments with different models to assess the possible range of land use change impacts on climate.

The significance of anomalies has been assessed on a grid point basis (Figure 2a and 2b) through a pool permutation procedure (PPP, *Preisendorfer and Barnett* [1983]). This technique requires having an ensemble of simulations. In this study, the same SST forcing is used every year (only the seasonal cycle is taken into account), thus each simulated year can be considered as an independent realization. The permutation procedure is consequently applied given 30 samples of each experiments and 1000 permutations were generated to produce a sample distribution. Table 1 indicates the percentage of grid points with significant change for each level of significance. This suggests that we obtain more significant anomalies than what should be obtained by chance. When performing the same experiment with a control climate of the 21st century, we obtain very similar patterns of anomalies (Figure 2b) over Africa, Asia, and northern mid-latitudes. The main difference is a weaker cooling over Siberia, which does not spread to the Pacific coast. The quite high correlation between the two patterns of figures 2a and 2b (table 2) emphasizes the robustness of the impacts.

4. Magnitude of the response to land-use changes compared to GHGs increase.

Figure 2c shows the impact of changing the GHGs concentrations using the same color-scale (not linear) as for figures showing the impact of land-cover changes (figures 2a and 2b). The impact of realistically changing land-cover is clearly of second order as compared to the impact of changing GHGs concentrations. Nevertheless, where the impact of land-cover change is significant, its magnitude exceeds 10% of the magnitude of the GHGs impact (figure 3). There are even some locations in Africa where the ratio reaches more than 30%. The impact of the GHGs concentrations increase is thus dominant, though it is modulated locally by the land cover change impact. This modulation is particularly important over Africa

for this scenario: the change in temperature is reduced over equatorial Africa and increased over the southeastern Africa when considering both effects simultaneously (figure 2d) as compared to the case with only GHGs (figure 2c). The same conclusions can be drawn when considering other climate parameters such as precipitation, evaporation or radiative fluxes.

Compared to the study of *Pitman and Zhao* [2000], the ratio of the impact of land cover change to the impact of GHG change is weaker. However, *Pitman and Zhao* [2000] have simulated past land cover changes. Thus the difference in the ratio could reflect that past land-use changes were relatively more important than projected future land cover changes. On the other hand, the difference in the ratio could correspond to a difference in model sensitivities.

The weak dependence of the impact of land use change to the GHGs concentration level of the control climate and its weak amplitude compared to the impact of GHGs concentration increase indicate that the climate impact of future land cover changes can be assessed independently of the GHGs effect.

5. Concluding remarks

This set of experiments demonstrates that the inclusion of land-cover evolution is important at the regional scale. On the other hand, the very high spatial correlation between figures 2c and 2d denotes that globally, the impact of GHG concentration change dominates over the impact of land cover change. Locally, the amplitude of land cover change can reach 30% of the GHGs impact. This demonstrates that land cover evolution has to be considered in regional scale studies. Our study also suggests that the impact of GHGs and land cover change can be assessed independently and both effects linearly added. However, such methods do not consider the possible feedback of subsequent climate change on land cover projections. The IMAGE model takes into account climate change and CO₂ increase over the 21st century to simulate land cover changes; nevertheless, the change in climate due to land cover conversions is not assessed. Possible feedbacks between the vegetation changes and climate could occur if the IMAGE model and a GCM were interactively coupled in a scenario simulation.

Moreover, this study suffers from several shortcomings. Firstly, the version of the land surface scheme used, ISBA, does not simulate photosynthesis, thus the physiological impact of vegetation changes is not fully assessed. Under higher CO₂ concentrations, stomatal resistance could be increased and then evaporation could be reduced more drastically. Secondly, climatological SSTs have been used for this study so the inter-annual variability of climate is not properly taken into account. *Voldoire and Royer* [2004] have already shown that the impact of vegetation changes could be more important on inter-annual variability than on the mean climate. Moreover, *Zhao and Pitman* [2002a] have shown that land cover conversions could affect the sensitivity to GHGs when considering extremes. The conclusion of this study is thus limited to the mean climate point of view. Thirdly, ocean feedbacks may also be important to understand the climate response to vegetation changes over some specific regions [*Delire et al.* [2001]].

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Figure 1. Land cover map simulated by IMAGE for 1980 (on left), and changes operated on the 2050 land cover map (on right) as compared to 1980.

Figure 2. Mean annual anomalies of near surface temperature for (a) the change in land-cover map keeping GHGs concentrations to 1980, (b) the change in land-cover map keeping GHGs concentrations to 2050, (c) the change in GHGs keeping the land cover map for 1980 and (d) both change in land-cover and GHGs concentrations. For (a) and (b), numbers 1,2 and 3 indicate significant anomalies at the 90%, 95% and 99% levels, for (c) and (d) all grid points have statistically significant anomalies.

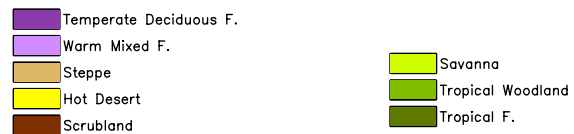
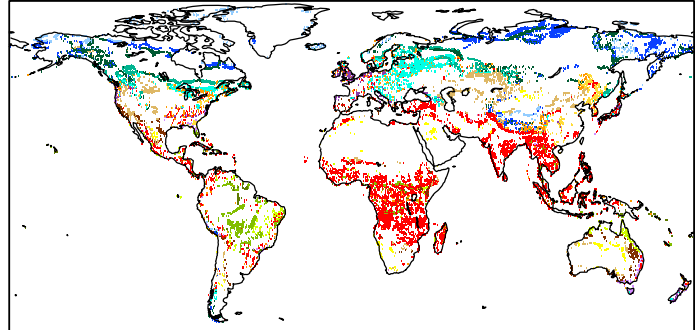
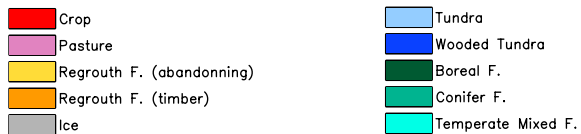
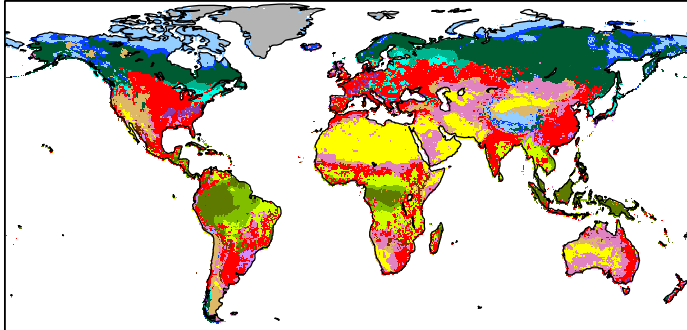
Figure 3. Ratio of the magnitude of the near surface temperature response to land cover change over the magnitude of the response to GHGs concentrations increase, e.g. $\frac{|LU_{2050}-CTL|+|GLU_{2050}-GCTL|}{|GCTL-CTL|+|GLU_{2050}-LU_{2050}|}$

Table 1. Percentage of land grid points with significant anomalies for each significance level on figures 2a and 2b.

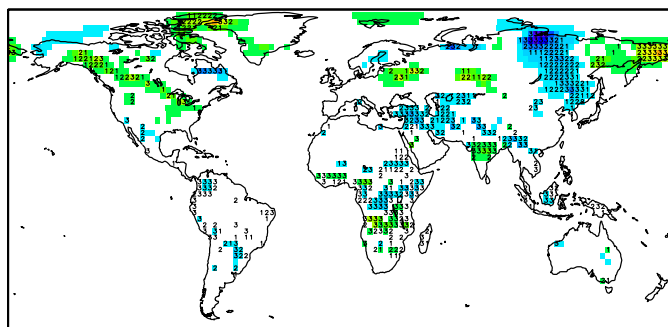
Confidence level	90%	95%	99%
LU2050-CTL (a)	26%	21%	13%
GLU2050-GCTL (b)	31%	24%	15%

Table 2. Spatial correlation calculated only over land points between patterns of temperature on figure 2.

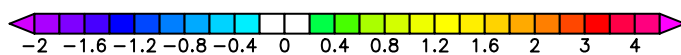
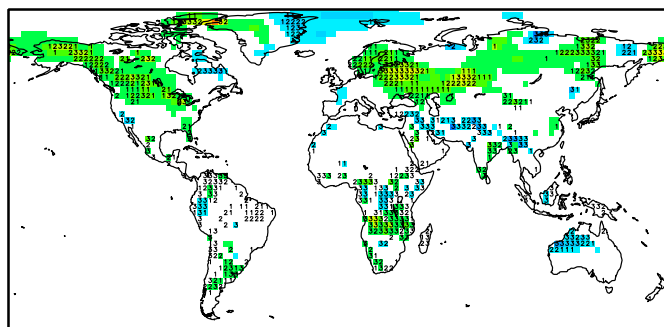
	(a)	(b)	(c)	(d)
(a)		0.58	0.11	0.25
(b)			0.19	0.44
(c)				0.97



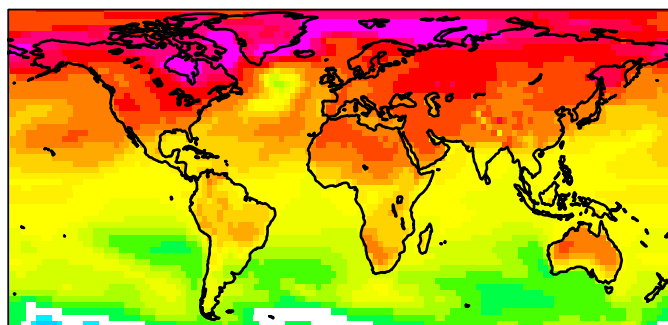
(a) LU2050-CTL



(b) GLU2050-GCTL



(c) GCTL-CTL



(d) GLU2050-CTL

