Biogeosciences Discussions

A model investigation of vegetation-atmosphere interactions on a millennial timescale

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Abstract

A terrestrial biosphere model with dynamic vegetation capability, Integrated Biosphere Simulator (IBIS), coupled to the NCAR Community Atmosphere Model (CAM2) is used to investigate the multiple climate-forest equilibrium states of the climate system. A 1000-yr control simulation and another 1000-yr land cover change simulation that consisted of global deforestation for 100 yr followed by re-growth of forests for the subsequent 900 yr were performed. After several centuries of interactive climate-vegetation dynamics, the land cover change simulation converged to essentially the same climate state as the control simulation. However, the climate system takes about a millennium to reach the control forest state. In the absence of deep ocean feedbacks in our model, the millennial time scale for converging to the original climate state is dictated by long time scales of the terrestrial carbon stocks, biomass and soil carbon. Our idealized modeling study suggests that the equilibrium state reached after complete global deforestation followed by re-growth of forests is unlikely to be distinguishable from the control climate. The real world, however, could have multiple climate-forest states since our modeling study is unlikely to have represented all the essential ecological processes (e.g. altered fire regimes, seed sources and seedling establishment dynamics) for the re-establishment of major biomes.

1 Introduction

Deforestation has both biogeochemical and biogeophysical influences on the climate: besides releasing carbon from land to the atmosphere (a biogeochemical effect), deforestation also has biogeophysical effects such as changes in land surface albedo, surface roughness, surface energy fluxes, and cloud cover (Betts et al., 1996; Govindasamy et al., 2001; Betts 2001; Brovkin et al., 1999, 2006, 2009; Feddema et al., 2005; Bala et al., 2007; Bonan, 2008; Findell et al., 2009). Thus, land cover changes alter the climate through physical, chemical, and biological processes and thereby could affect temperature, the hydrologic cycle, and atmospheric composition.

Recently, Davin and Noblet-Ducoudre (2010) found that the biogeophysical (i.e. albedo change and evapotranspiration) impact of global deforestation leads to global cooling of 1K because the albedo effect is dominant over evapotranspiration. Lawrence and Chase (2010) and Xu et al. (2009) found that for land cover change surface hydrology and its interaction with vegetation and soils also has large impacts on the climate. Changes in land cover can also have remote effects: Chen et al. (2001), Snyder et al., (2004) and Avissar et al. (2004) have found that tropical deforestation is likely to induce changes in atmospheric circulation, and that these changes may have consequences on precipitation and temperature patterns on a global scale.

In view of the aforementioned discussion on the climate effect of land cover change there is a need to understand the impact of large perturbations to land cover. Are there interactions between forests and the atmosphere (i.e. vegetation-precipitation feedback) that gets severely altered for large scale land cover change? Specifically, if deforested areas are abandoned and forests are allowed to re-grow, will the climate system go back to its natural state? How long will it take for the climate system to reach a new equilibrium in such a case? What determines the time scale? We will address these questions in this paper using a dynamic vegetation model coupled to an atmospheric general circulation model. Our model has representation for dynamic vegetation, interaction between atmosphere and land surface via precipitation, soil moisture and plant water uptake but it lacks detailed representation for nitrogen cycle, evolution of atmospheric CO_2, disturbance such as fires and pests, anthropogenic land cover change, and management of forests. Therefore, our investigation mainly aims to find out if interaction among atmosphere, land biophysics and dynamic natural potential vegetation will result in multiple equilibriums.

Multiple steady states in the atmosphere biosphere system can arise as a consequence of positive feedbacks between atmosphere and land surface. Claussen (1994, 1998) and Claussen et al. (1998) find that multiple equilibrium vegetation–climate states can exist in the present-day semi-desert regions of northern Africa and western Asia. A modeling study by Levis et al. (1999) and Brovkin et al. (2003) find only

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one possible stable steady state in the climate system in the high latitudes while bi-stable vegetation-climate states are found in models for the Amazon by Oyama and Nobre (2003), and for Central-Asia and North-Africa by Claussen (1998). Wang and Eltahir (2000) study the stability of similar states in response to disturbances. Brovkin et al. (1998) uses a conceptual model to compare desert versus "green" equilibrium under parameter estimates typical of current climate and of mid-Holocene climate, re-spectively.

The possibility of multiple forest-climate states in the climate system has been in-vestigated recently by Brovkin et al. (2009) in the Earth System Model of the Max Planck Institute for Meteorology (MPIESM). In their study, when the geographic dis-tributions of vegetation in forest-only and grassland-only simulations are allowed to interactively respond to climate, both forest and grassland simulations converge to es-sentially the same climate state as in the control simulation after subsequent 500 yr of interactive climate-vegetation dynamics. This convergence suggests an absence of multiple climate-forest states in MPIESM. Dekker et al. (2010), using an Earth Model of Intermediate Complexity, PlaSim, find that model integrations starting from different initial biomass distributions diverge to clearly distinct climate-vegetation states in terms of climatic (precipitation and temperature) and biotic (biomass) variables. Their simu-lations suggest that the boreal and monsoon regions have low resilience, i.e. unstable biomass equilibrium with positive vegetation-climate feedbacks in which the biomass change induced by a perturbation is further enhanced. Large perturbations trigger an abrupt shift of the system towards another steady state, and hence, Dekker et al. (2010) stress the importance of coupling at multiple scales in vegetation-climate models and indicate the urgent need to understand the system dynamics for improved projections of ecosystem responses to anthropogenic changes in climate forcing.

In the present study, we investigate the possibility of multiple states in the climate system by carrying out transient simulations using the NCAR atmospheric general cir-culation model CAM (Community Atmosphere model) coupled to a dynamic vegetation model and a mixed layer ocean model. Our study is the first that performs a millennial

time scale simulation using a *comprehensive coupled atmospheric general circulation model and a terrestrial biosphere model* to investigate the possibility of multiple states. We show that the climate-vegetation system has no multiple steady states in this modeling study but it takes nearly a millennium for the system to return to the initial equilibrium state due to long time scales of biomass and the soil carbon. As a caveat, we note that our simulations are idealized and intended to understand the earth system behavior for possible multiple climate-forest states. This study is not intended to realistically represent current or future land cover change

2 Model description

The coupled climate-vegetation model used is Integrated Biosphere Simulator (IBIS)(Foley et al., 1996; Kucharik et al., 2000) coupled to Community Atmosphere Model 2.0 of NCAR (CAM2) (Collins et al., 2004). We used the finite volume configuration of the model with a horizontal resolution of 2° latitude and 2.5° longitude. There are 26 vertical levels. For this study, we coupled CAM2 to a mixed layer ocean and thermodynamic sea ice model, which allows for interactive surface for the ocean and sea ice components of the climate system.

Land surface biophysics, terrestrial carbon flux and global vegetation dynamics are represented in a single, physically consistent modelling framework within IBIS. IBIS simulates a variety of ecosystem processes including energy, water, and carbon dioxide exchanges between soil, plants and the atmosphere, physiological processes of plants (photosynthesis and respiration), soil biogeochemistry, vegetation phenology including budburst, senescence, and dormancy of vegetation, plant growth and competition, nutrient cycling and soil physics. The coupled simulation of surface water, energy and carbon fluxes are performed on hourly time steps and integrated over the year to estimate annual water and carbon balance. The annual carbon balance of vegetation is used to predict changes in the leaf area index and biomass for each of 12 plant functional types, which compete for light and water using different ecological strategies.

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IBIS also simulates carbon cycling through litter and soil organic matter. When driven by observed climatological datasets, the model's near-equilibrium runoff, net primary productivity (NPP), and vegetation categories show a fair degree of agreement with observations (Foley et al., 1996, Kucharik et al., 2000).

3   Experiments

We first performed a long simulation with prescribed climatological sea surface temperatures (SST) and a round number of present day CO_2 concentration of 400 ppm to calculate the implied ocean heat transport which is needed to use CAM2 in slab ocean configuration. For this climatological-SST simulation, we used a soil carbon spin up factor of 40 and ran the model until biomass and soil carbon reached quasi equilibrium. A soil carbon drift of less than 0.1 Gt-C per year is used to define the quasi equilibrium state. The implied ocean heat transport is calculated after soil carbon reached equilibrium. Then, we used this spun-up state of the biosphere model in a 200 yr mixed layer simulation until the soil carbon again reached quasi equilibrium. From this state, we performed two 1000-yr mixed layer simulations as described below.

(1) a control simulation corresponding to present day conditions, (2) a land cover change simulation, denoted by "LCC", where we do not allow tree plant functional types (PFTs) to exist globally for 100 yr; only grasses and shrubs are allowed. The biomass in tree leaves and fine roots is immediately (year 1) transferred to the litter pool, and the stem biomass becomes litter on a time scale of 10–50 yr depending on the tree plant functional type. After 100 yr, all PFTs are allowed to exist for the subsequent 900 yr. By 100 yr, majority of the biomass would be transferred to the litter pool and hence we choose this time scale for the deforested period. We choose 900 yr for the re-growth period because that is the time it took for the coupled vegetation- climate system in this model to reach a quasi equilibrium state. The climate statistics presented below are the averaged values over the last 100 yr of model simulations. The statistical significance here is tested using the student t-test with correction for lag-1 autocorrelation (Zwiers and von Storch, 1995).

Since our model is not a comprehensive earth system model with deep-ocean and ocean carbon cycle, we do not have the formulation for tracking the carbon and accounting for the carbon budget in this study. We have prescribed atmospheric CO_2 at a constant level (400 ppm) throughout the simulation period and hence it serves as an infinite reservoir for carbon for the terrestrial biosphere. In effect, we account for feedbacks due to biophysical effect of land cover change (e.g. albedo, evapotranspiration, roughness length changes) but omit the biogeochemical change since atmospheric CO_2 does not vary in response to land cover change.

4 Results

The temporal evolution of global and annual mean key climate and terrestrial carbon cycle variables is shown in Fig. 1. In response to the instantaneous deforestation in LCC simulation, the surface temperature decreases by 1.7 K averaged over the first 100 yr and global mean precipitation decreases by 3.7 %. The sign of the changes are suggestive of the dominance of albedo effect (deforestation increases the surface reflectivity) over changes in evapotranspiration and the associated cloud effects in this model. Temperature change simulated in our study is comparable to another global land cover change study that included only biogeophysical effect (1.3 K in Gibbard et al., 2005) but higher than obtained in Bala et al., (2007) because this later study also included the warming effect of increased atmospheric CO_2 from deforestation (the carbon cycle effect).

When tree-PFTS are allowed from the deforested state, temperature and precipitation and other variables show a fast recovery for about 100 yr (Fig. 1) followed by a slow recovery for the subsequent centuries . After 700 yr of model integration with interactive climate-vegetation dynamics from the deforested state, the global mean annual surface temperature and precipitation in the LCC simulation slowly converges to essentially the same climate state (Fig. 1a–b) as that of control simulation. Global mean surface temperature in LCC, averaged over the last century, is higher than the control state by only

0.08 °C. Since the standard deviation in the control is of the same magnitude (0.07 °C in control and 0.09° C in LCC), we conclude that the climate of the last hundred years of LCC are indistinguishable from the control.

However, the time series of carbon cycle variables specifically the carbon stocks (Fig. 1c–d), suggest that the terrestrial biosphere is still converging towards the new equilibrium state. Immediately following deforestation, Net Primary Productivity (NPP) declines by 22 % from 79 to 62 Gt-C per year since grasslands have, on an average, less NPP than forests in this model (Fig. 1e). The step like behavior of NPP at year 100 is due to rapid increase in gross primary productivity since tree PFTs have higher LAI than grasses and shrubs. Net Ecosystem Exchange (NEE) represents the net land carbon uptake and is defined as NPP minus soil respiration which includes both microbial decomposition and root respiration. It shows declines and increases of similar magnitude to NPP after instantaneous deforestation and immediately following re-growth of forests (Fig. 1f). The sharp decline of NEE by 18 Gt-C immediately after deforestation is mainly due to the sharp decline in NPP. The subsequent increase in NEE is mainly due to decrease in soil respiration (Fig. 1g). Re-growth of forests at year 100 leads to a jump in NEE because of the step-function-like increase in NPP. Subsequently, increase in soil respiration leads to the decline in NEE to control simulation levels. The time scale of NEE recovery is about 100 yr which is primarily dictated by the decomposition time scale of dead stem biomass in the litter pool (Fig. 1h).

After deforestation, there is a large decline of about 800 Gt-C in biomass (Fig. 1c). Soil carbon increases(Fig. 1d) by only about 120 Gt-C during this period because most of the dead biomass is transferred to the litter pool which transfers only a fraction to soil carbon pool and the rest decomposes from the litter pool. When forests are allowed to re-grow, there is a rapid recovery in biomass; it increases from less than 100 Gt-C to more than 800 Gt-C within 100 yr. After this period, it asymptotically reaches the control simulation after several centuries. Soil carbon stock also shows a rapid recovery but it has about 20 Gt-C more than control even after 900 yr of re-growth. It should be noted that there is no conservation of total carbon stock (biomass plus soil carbon) in

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this study because atmospheric CO_2 is prescribed, providing an infinite reservoir for carbon to the terrestrial biosphere.

The spatial pattern of temperature change in LCC relative to control averaged over the last 100 yr shows that the changes in the boreal winter are large in high latitudes but not statistically significant (Fig. 2). Changes are much smaller in the JJA season and again not statistically significant. Only 1.6 and 1.7 % of the globe have significantly different temperature in LCC relative to control in DJF and JJA seasons, respectively, at 5 % significance level. Changes in precipitation are shown in Fig. 2c and 2d. The LCC simulation produces in general more precipitation over land than the control simulation during both the DJF and JJA seasons (Fig. 2c). However, like temperature changes, precipitation changes are also not significant in most places. Only 3.1 and 4.5 % of the globe have significantly different precipitation in LCC relative to control in DJF and JJA seasons, respectively, at 5% significance level. In summary, Fig. 2 shows that spatial pattern of the physical (abiotic) climate system in LCC is almost indistinguishable from the control.

Figure 3 shows NPP, biomass and soil carbon in the LCC and control simulations and their difference averaged over the last 100 yr. In the control and LCC simulations, NPP and biomass are larger in thickly vegetated regions of the world such as Amazon, central Africa, South and Southeast Asia, Europe and eastern North America. There is a large bias in simulated NPP and biomass in Australia when compared to a standard suite of global products characterizing the NPP based on satellite observations (Fig. 5 in Running et al., 2004). Soil carbon is also higher in places where NPP and biomass have larger values. In addition, soil carbon has maxima in colder places such as Siberia, Alaska and the Himalayas. The spatial pattern of NPP, biomass and soil carbon is similar in both control and LCC simulations. Differences in these variables are small and mostly not significant except soil carbon differences in some high latitude locations in Siberia and Alaska: the differences in NPP, biomass and soil carbon are significant over 3.9, 21.3, and 25.2 % of the land regions. Since the magnitudes of the differences are small, we conclude that the spatial distribution of the terrestrial carbon

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fluxes and carbon stocks (biotic component) in LCC in the last 100 yr are also almost indistinguishable from control.

The percentage of simulated dominant vegetation types in the last 100 yr in LCC and control cases are given in Table 1. We found that the model simulates the locations of major biomes reasonably well; tropical evergreen and deciduous forests in the tropics, temperate forests in the mid latitudes and boreal forests in the high latitudes. However, there were major biases such as the simulation of tropical and temperate forests in desert regions such as Saudi Arabia, Australia and northern Africa and, consequently, an underestimation of deserts, Tundra and polar desert regions. We identified that a warm and wet bias in the control simulation was the main cause for these biases: the global and annual mean surface air temperature and precipitation in the control simulation are higher by 1.3 °C and 10 % when compared to NCEP reanalysis (Kistler et al., 2001) and GPCP (Adler et al., 2003), respectively.

We use kappa statistics (Monserud, 1992) to compare vegetation distributions in LCC and control. Kappa takes on a value of 1 with perfect agreement. It has a value close to zero when the agreement is approximately the same as would be expected by chance. Global comparison of vegetation distributions of LCC and control gives a kappa value of 0.93 (excellent agreement). Except for Tundra, Kappa for major biomes between LCC and control suggests either excellent or very good agreement (Table 1). This suggests that the spatial distribution of the vegetation state in LCC in the last 100 yr is also almost indistinguishable from control.

5 Discussion

In this study, we examined the possibility of multiple climate-forest states using a terrestrial biosphere model IBIS2 coupled to NCAR CAM2. For this purpose, we performed a global deforestation experiment for 100 yr followed by re-growth of forests. We find that there are no multiple climate-forest states in our model; the simulation with deforestation followed by re-growth converges to the control climate. Our conclusion is similar to a recent modeling study (Brovkin et al., 2009) which also found an absence

of multiple climate-forest states in the Earth System Model of the Max Planck Institute for Meteorology, but different from another study by Dekker et al. (2010) which found multiple equilibrium states. In our study, we find that the climate system takes about 700 yr to come back to the original natural state. This is despite the fact that our sim-
ulation did not have representation for deep ocean feedbacks; we have used only a mixed layer ocean model for representing the interaction between the atmosphere and oceans. The millennial time scale for recovery in our model is dictated by soil carbon and biomass which take several centuries to reach a new equilibrium state.

The dynamic vegetation model used in this study has some limitations: IBIS does
not have representation for nitrogen and other nutrient cycles (Cramer et al., 2001; McGuire et al., 2001; Bala et al., 2007). IBIS model, in its current form, does not include a dynamic fire module (Foley et al., 1996). It does not account for changes in pest attack or grazing by animal in a changed climate. Suitable climatic conditions are sufficient for the existence of plant functional types in IBIS: seed dispersal mechanisms
which are crucial for reestablishment of forests are not represented. The real world, therefore, could have multiple climate-forest states, and this present modeling study is unlikely to have represented all the essential ecological processes (such as altered fire regimes, seed sources and seedling establishment dynamics) for the re-establishment of major biomes.

The occurrence of multiple equilibriums in some models could be a model artifact, caused by discrete vegetation classes (Kleidon et al., 2007) since multiple steady states occur in models only if vegetation is represented by a few vegetation classes. Kleidon et al. (2007) found, with an increased number of classes, the difference between the numbers of multiple steady states diminishes and disappears completely in
the model when vegetation is represented by 8 classes or more (we have 12 vegetation types in this modeling study). Therefore, our modelling study results with 12 PFT's also leads to no multiple steady states. An analysis of the sensitivity of multiple equilibriums to parameters in the model is beyond the scope of this paper and our future studies will investigate this.

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Major limitations of this modelling study are the lack of deep-ocean dynamics, dynamic sea ice, and representation of biogeochemical effects of vegetation cover changes and ocean carbon cycle. As discussed before, the effect of changes in atmospheric CO_2 from deforestation and interactive vegetation is not modeled in this study. For instance, we have overestimated the amount of cooling immediately after deforestation on shorter time scales because we have not included the effect of CO_2 emission from deforestation. However, on centennial to millennial time scale the ocean biogeochemistry could buffer most of the atmospheric CO_2 changes induced by an altered land cover. Future modelling on the investigation of multiple climate-forest states should use coupled climate and carbon cycle models that will have realistic representation of these long term feedbacks in the climate system.

The results discussed in this paper are from a single modelling study. Climate model differ in their representation of physical processes and hence models show differing sensitivities to climate perturbations. Many of the local and remote effects depend heavily on the model structure and the simulated effects are therefore subject to have a wide range. Therefore, an intercomparision of multiple models in the future will be required to investigate robustness in the behaviour climate system.

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A model investigation of vegetation-atmosphere interactions

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Interactive Discussion

Table 1. Areal extent of dominant vegetation types and Kappa statistics.

Dominant Vegetation type	Control (%)	LCC (%)	Kappa Statistics	Degree of Agreement
Tropical Evergreen	22.8	22.9	0.96	Excellent
Tropical deciduous	13.8	13.8	0.93	Excellent
Temperate	20.9	20.5	0.95	Excellent
Boreal	12.0	12.1	0.85	Excellent
Savana, Grasslands and Shrublands	15.0	14.1	0.83	Very good
Tundra	3.2	3.9	0.39	Poor
Desert	4.8	5.0	0.95	Excellent
Ice	7.5	7.7	0.81	Very good
Global Vegetation	100	100	0.93	Excellent
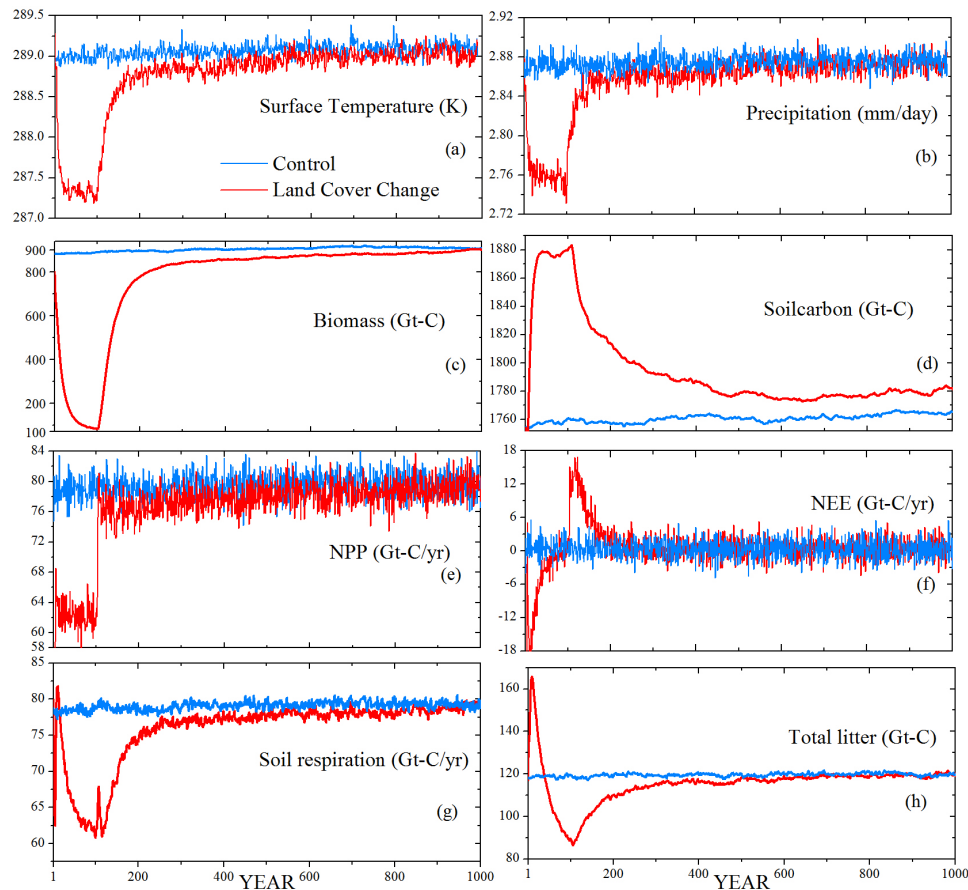
Fig. 1. Evolution of global and annual mean **(a)** surface temperature, **(b)** precipitation, **(c)** biomass, **(d)** soil carbon, **(e)** net primary productivity (NPP), **(f)** net ecosystem exchange (NEE), **(g)** soil respiration (includes heterotrophic respiration and disturbances), and **(h)** total litter for the 1000-yr control and LCC simulations.
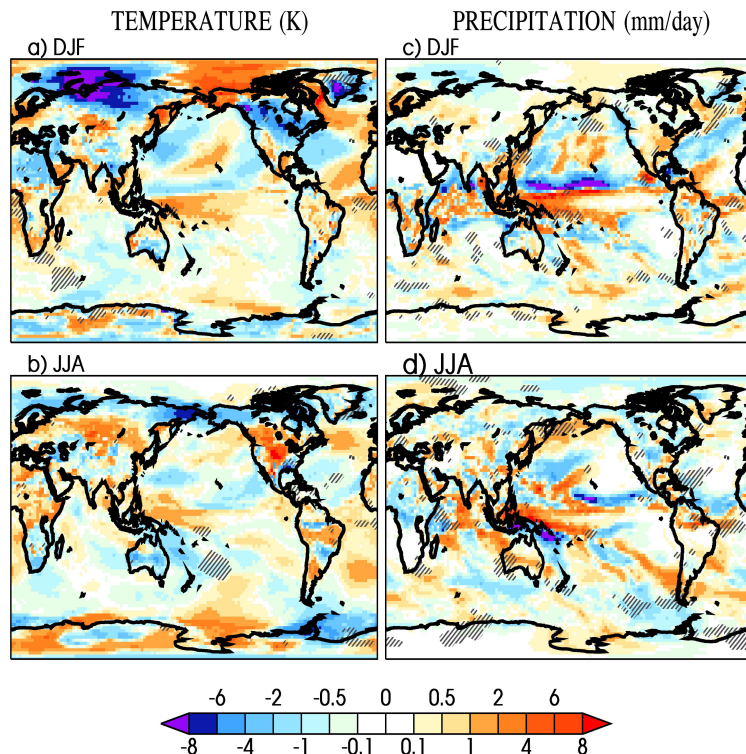
Fig. 2. Mean differences between LCC and control simulations for surface Temperature (°C) in **(a)** winter (DJF), **(b)** summer (JJA), and precipitation (mm day^{-1}) in **(c)** winter (DJF), and **(d)** summer (JJA). Mean differences are obtained by averaging over the last 100 yr. Hatched areas are regions where changes are statistically significant at the 95 % confidence level. Significance level is estimated using a Student-t test with a sample of 100 means and standard error corrected for autocorrelation (Zwiers and von Storch, 1995).
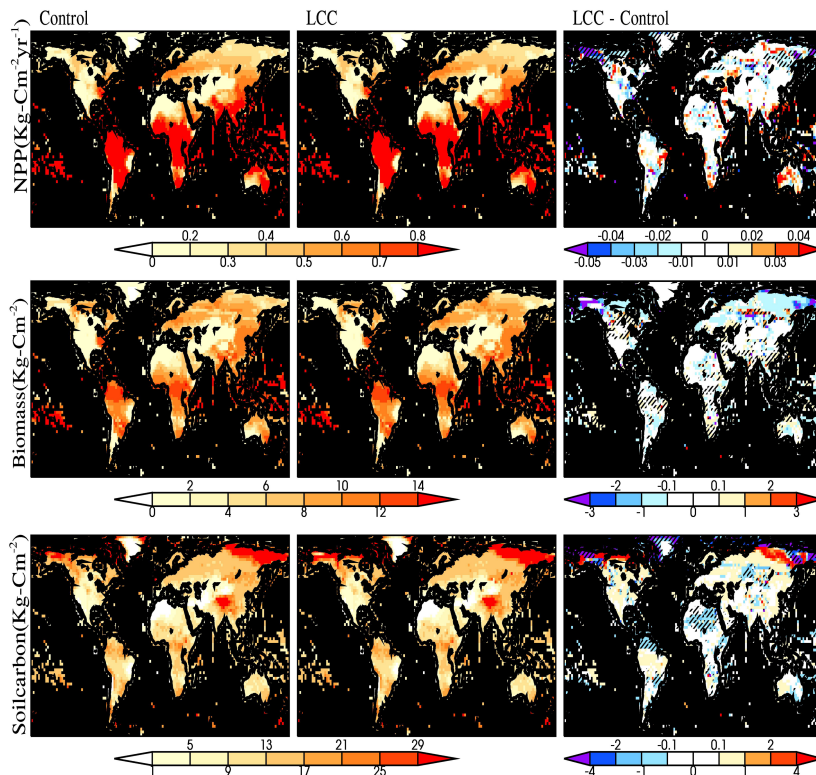
Fig. 3. Comparison between LCC and control simulations for terrestrial biosphere variables. The first and second column panels represent 100-yr mean from the control and LCC simulations, respectively. The third column panels represent the difference between LCC and the control simulations. Hatched areas are regions where changes are statistically significant at the 95 % confidence level. Significance level is estimated using a Student-t test with a sample of 100 means and standard error corrected for autocorrelation (Zwiers and von Storch, 1995).

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