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Biogeophysical versus biogeochemical climate response to historical anthropogenic land cover change

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[1] Anthropogenic land cover change (ALCC) is one of the few climate forcings with still unknown sign of their climate response. Major uncertainty results from the often counteracting temperature responses to biogeochemical as compared to biogeophysical effects. Here, we separate the strength of these two effects for ALCC during the last millennium. We add unprecedented detail by (i) using a coupled atmosphere/ocean general circulation model (GCM), and (ii) applying a high-detail reconstruction of historical ALCC. We find that biogeophysical effects have a slight cooling influence on global mean temperature (−0.03 K in the 20th century), while biogeochemical effects lead to strong warming (0.16–0.18 K). During the industrial era, both effects cause significant changes in certain regions; only few regions, however, experience biogeophysical cooling strong enough to dominate the overall temperature response. This study therefore suggests that the climate response to historical ALCC, both globally and in most regions, is dominated by the rise in CO_2 caused by ALCC emissions. **Citation:** Pongratz, J., C. H. Reick, T. Raddatz, and M. Claussen (2010), Biogeophysical versus biogeochemical climate response to historical anthropogenic land cover change, *Geophys. Res. Lett.*, *37*, L08702, doi:10.1029/2010GL043010.

1. Introduction

[2] Anthropogenic land cover change (ALCC) represents one of the few climate forcings for which it is still not known whether they impose a global cooling or warming effect. The analysis is complex because ALCC affects biosphere-atmosphere fluxes through a multitude of partially counteracting processes, generally grouped into biogeophysical and biogeochemical mechanisms.

[3] Biogeophysical mechanisms describe the influence on climate by the modification of the physical properties of the land surface such as albedo, roughness, and evapotranspiration (ET). Modeling studies suggest that through this biogeophysical pathway, past ALCC at high to midlatitudes induces a cooling, which is driven by the increase in surface albedo with deforestation in particular in the presence of snow [e.g., *Claussen et al.*, 2001; *Bounoua et al.*, 2002]. The reduction in ET with ALCC is more pronounced in the tropics due to the strong hydrological cycle, and may lead to local warming [e.g., *Claussen et al.*, 2001; *Bounoua et al.*, 2002; *DeFries et al.*, 2002]. Remote areas may be affected via teleconnections [e.g., *Zhao et al.*, 2001].

[4] Probably the most important biogeochemical mechanism of ALCC for global climate is the influence on the carbon cycle, and the associated impact on the global atmospheric CO_2 concentration. Coupled simulations quantified an ALCC-induced increase of CO_2 by about 18–20 ppm over the last millennium, as result of ALCC emissions of around 160 GtC and subsequent uptake by the ocean and the land biosphere [*Brovkin et al.*, 2004; *Pongratz et al.*, 2009b]. While the biogeophysical effects of ALCC influence climate more strongly on the local scale, the biogeochemical effects are felt globally since atmospheric CO_2 is well mixed.

[5] Only few studies have compared biogeophysical and biogeochemical effects consistently using the same model. The few that did so applied Earth system models of intermediate complexity (EMIC): sensitivity studies of complete deforestation and afforestation in zonal belts have been performed by *Claussen et al.* [2001], and future scenarios have been investigated by *Sitch et al.* [2005]. Historical ALCC has been assessed only by *Matthews et al.* [2004] for the last 150, and *Brovkin et al.* [2004] for the last 1000 years. However, their conclusions concerning the full or "net" effect of biogeophysical and biogeochemical mechanisms are contradictory, with a net cooling of −0.05 K found by *Brovkin et al.* [2004] and a net warming of 0.15 K found by *Matthews et al.* [2004].

[6] In the present study, we try to give an improved estimate of the strength of the two individual effects and determine the sign of the net effect. We go beyond previous studies in two respects: First, we couple our land surface scheme to a general circulation model (GCM) for atmosphere and ocean. This implies both more process detail than EMIC studies and a higher spatial resolution. The latter is crucial to capture realistically the effects of a heterogeneous forcing such as ALCC. Second, we apply a detailed reconstruction of ALCC over the last millennium (due to earlier lack of such data, *Brovkin et al.* [2004] assumed a state of potential vegetation in the year AD 1000). All our simulations run transiently over the last millennium, including biosphere-atmosphere feedbacks and the closed, interactive carbon cycle. The latter is important to capture the accumulation of atmospheric CO_2 from ALCC emissions over time. To our knowledge, this is the first GCM study that simulates ALCC effects on a millennium timescale and separates biogeochemical from biogeophysical effects consistently.

2. Model Simulations

[7] Our GCM consists of ECHAM5 [*Roeckner et al.*, 2003] at T31 (approximately 4 degree) resolution with 19 levels in

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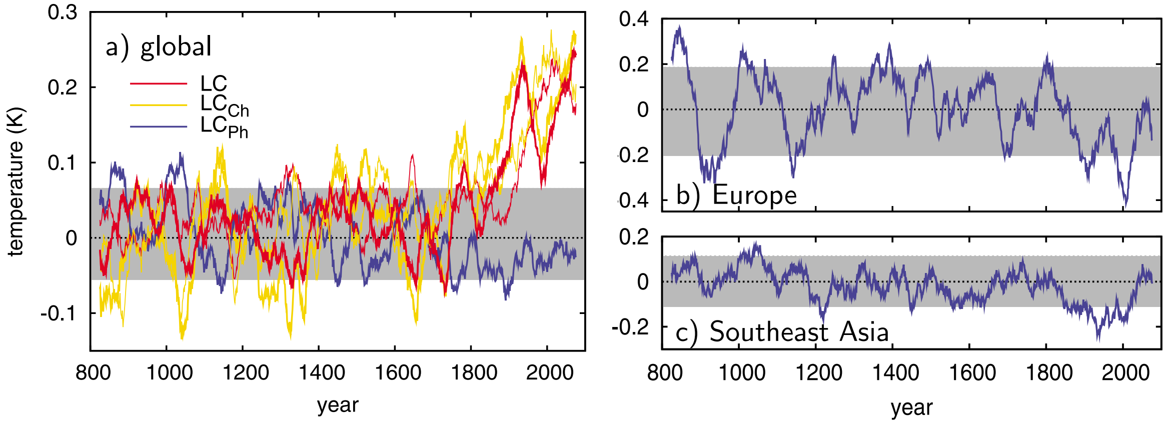

Figure 1. Changes in annual mean surface temperature from ALCC (50-years running mean). (a) Global mean temperature change. LC_{Ph}: biogeophysical effects; LC_{Ch}: biogeochemical effects; LC: net effect. Thick lines are best-guess ALCC, thin lines are high land cover dynamics. The shaded area indicates the 5–95 percentile of the control simulation for the net effect. Biogeophysical effects for (b) Europe (land area 0–50°E, 40–60°N) and (c) Southeast Asia (land area 67–120°E, 10–40°N).

the vertical representing the atmosphere, and MPI-OM [*Marsland et al.*, 2003] at 3 degree resolution with 40 levels in the vertical representing the ocean. It includes the closed, interactive carbon cycle simulated by the ocean biogeochemistry model HAMOCC5 [*Wetzel et al.*, 2005] and the modular land surface scheme JSBACH [*Raddatz et al.*, 2007]. JSBACH distinguishes 12 plant functional types (PFTs), including one crop type, which differ with respect to prescribed parameters from which phenology, morphology, and photosynthesis are calculated in response to climate. The fractional coverage of PFTs within each grid cell is prescribed from maps annually. In this study, the vegetation maps contain the evolution of ALCC caused by agricultural activity (cropland and pasture) over the last millennium as described by *Pongratz et al.* [2008].

[8] This setup simulates the interaction of biosphere and atmosphere with feedbacks in both directions, e.g. with interactive phenology, transpiration, and albedo. Also carbon fluxes are interactive and the atmospheric CO_2 adjusts to the balance of carbon uptake and release by the terrestrial biosphere and the ocean. ALCC affects these interactions by modifying the biophysical land surface properties and by relocating vegetation and soil carbon between 5 different carbon pools, which leads to immediate and delayed CO_2 emissions [*Pongratz et al.*, 2009b].

[9] To separate biogeophysical and biogeochemical effects, the model code is changed such that the biogeophysical effects of ALCC are isolated. The biogeochemical effects are suppressed by (i) not allowing ALCC-related relocation of carbon between the terrestrial pools, and (ii) prescribing the constant land cover map of the year AD 800 to the calculations of canopy conductance for CO_2. Plant productivity and heterotrophic respiration therefore do not experience ALCC in this setup. On the other hand, canopy conductance for water as well as the calculations of the physical land surface properties such as albedo and roughness do adjust according to the prescribed changes in PFTs.

[10] Four simulations branch off from the equilibrium state of the year AD 800: Apart from a 1300-year-long control simulation, three transient simulations run until the year 2100, which all apply ALCC as the only forcing in order to isolate its effects on climate. The first simulation (named LC) uses the unaltered model code to include both biogeophysical and biogeochemical effects and all atmosphere-ocean-biosphere feedbacks. The second (LC_{Ph}) applies the modified model described above to simulate only the biogeophysical effects of ALCC including feedbacks. The difference $LC_{Ch} = LC - LC_{Ph}$ approximates the climate response to the biogeochemical effects of ALCC. To account for the large uncertainty in preindustrial land cover change, we run an additional simulation to LC in which we replace our "best-guess" ALCC reconstruction by one of maximum possible ALCC prior to AD 1700 [*Pongratz et al.*, 2008].

3. Results

[11] On the global scale, the annual mean temperature response to all effects of ALCC is a warming (Figure 1a); for the 20th century it amounts to 0.15 and 0.13 K (for best-guess ALCC and high land cover dynamics, respectively). This net effect includes a biogeophysical cooling of −0.03 K, and a biogeochemical warming of 0.18 K and 0.16 K.

[12] On the regional scale, the biogeophysical temperature response is much more important than suggested by its global mean. In Europe, North America, China, and India annual mean temperature is decreased by 0.3–0.5 K, while a warming is simulated for smaller regions in the tropics and subtropics (Figure 2a). The mentioned cooling in northern high and midlatitudes is largely albedo-driven, leading to a winter cooling of up to 0.9 K in Northeast Europe, in general accordance with previous studies [e.g., *Betts*, 2001]. The albedo dominance over hydrological aspects in this study is only pronounced, however, on the annual mean, because transpiration effects may be seasonally offsetting.

[13] ALCC in tropical and southern subtropical regions, on the other hand, leads to a warming, which has also been found in previous studies [e.g., *Bounoua et al.*, 2002]. In addition to a decrease of ET the warming is enforced by decreased cloud cover (not shown), counteracting the increase of surface albedo. In the northern subtropics (dominated by India), increases in albedo and higher ET partially caused by increased precipitation act in the same direction to

cause strong cooling on land (note that precipitation changes are likely more model-dependent [*Pitman et al.*, 2009] than albedo changes). Teleconnections lead to significant warming over the ocean and land areas remote from ALCC, in particular over Northeast Siberia, a pattern similarly found by *Zhao et al.* [2001].

[14] The spatial pattern of the biogeochemical temperature response resembles that from observed, greenhouse-gas-driven climate change over the last decades, with a strong warming in northern high latitudes due to the sea ice-albedo feedback (Figure 2b). Indeed, atmospheric CO_2 in the net simulation increases by 20 ppm over the last millennium as a result of gross emissions from ALCC of 161–171 Gt carbon [*Pongratz et al.*, 2009b]. Driven by the atmospheric concentration of well-mixed CO_2, the temperature response is unrelated to local effects of ALCC; thus, strong local biogeophysical effects can substantially influence the spatial pattern of the net temperature response, as seen e.g. in Eastern Europe/Central Asia and also in parts of India (Figure 2c). The latter is one of the few areas where the biogeophysical cooling is stronger than the biogeochemical warming, but the temperature signal is not statistically significant. The global vs. local effectiveness of biogeochemical vs. biogeophysical effects is also seen in Table 1: While the entire land area is more strongly influenced by the biogeochemical warming than the ocean, the biogeophysical cooling is particularly pronounced over the agricultural areas.

Table 1. Changes in Annual Mean Surface Temperature Caused by ALCC Averaged Over the 20th Century[a]

Simulation	Land	Ocean	Agricultural Area
LC_{Ph}	−0.04	−0.03	−0.10
LC_{Ch}	0.27 (0.24)	0.15 (0.14)	0.31 (0.25)
LC	0.22 (0.19)	0.12 (0.11)	0.21 (0.15)

[a] Changes in surface temperature for land, ocean, and agricultural area as found in this study. Annual mean surface temperature is given in K.

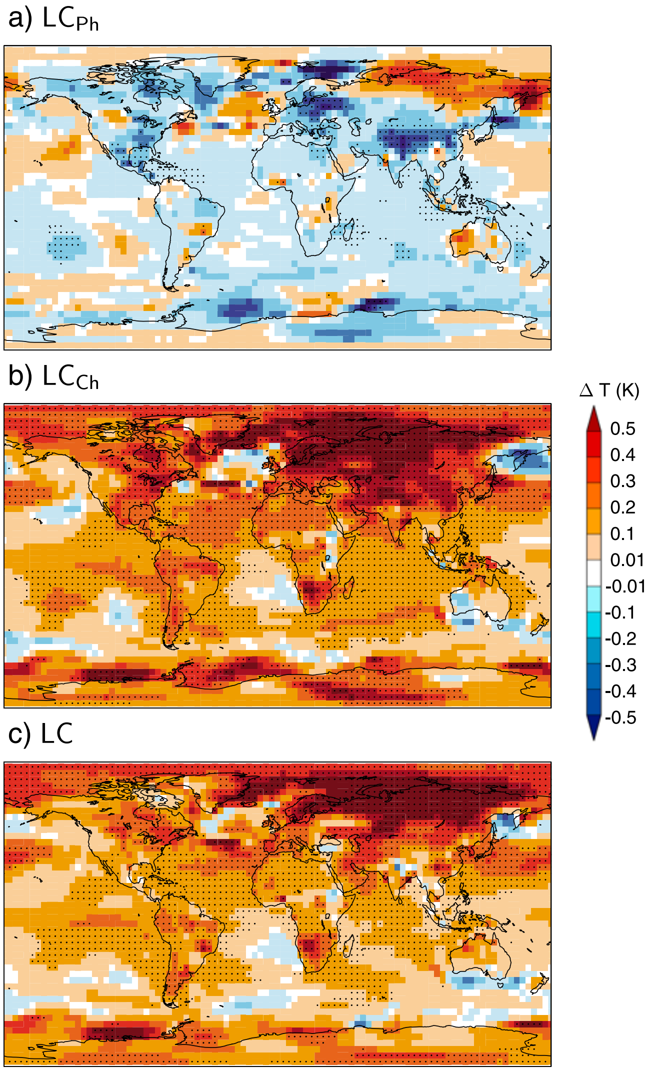

Figure 2. Change in annual mean surface temperature from ALCC averaged over the 20th century. LC_{Ph}: biogeophysical effects; LC_{Ch}: biogeochemical effects; LC: net effect. Areas significant at the 95% level of a modified Student's t-test accounting for temporal autocorrelation are dotted.

4. Discussion

[15] Table 2 compares our findings to the two EMIC studies that separated the biogeophysical and biogeochemical responses. The net temperature rise found in the present study is close to the estimate by *Matthews et al.* [2004]. Our GCM study therefore supports the notion that biogeochemical effects dominate over biogeophysical effects, and finds a similar strength for them as *Brovkin et al.* [2004]. However, our biogeophysical response is substantially weaker than both previous studies suggested, and also weaker compared to an intercomparison of 6 EMICs, which simulated a biogeophysical response of −0.13 to −0.25 K [*Brovkin et al.*, 2006].

[16] It has been noted before that EMICs tend to simulate a stronger biogeophysical response to ALCC than GCMs [*Brovkin et al.*, 2004]. Our study suggests several reasons for this: (1) Surface albedo changes are smaller in the GCM study in particular in the northern mid- to high latitudes (Figure S1b).[1] *Qu and Hall* [2007] showed that an albedo scheme as applied in ECHAM5/JSBACH, which includes an explicit treatment of vegetation canopy and vegetation coverage, generally leads to lower values under snowy conditions and to smaller albedo changes with temperature change than simpler albedo schemes. (2) The GCM simulates interactive cloud cover, similar to the study by *Brovkin et al.* [2004] but unlike *Matthews et al.* [2004] and most models of the EMIC intercomparison. Due to the reduced latent heat flux (Figure S1c) and reduced roughness, cloud cover decreases in our study over many agricultural areas, which offsets the increase in surface albedo with respect to absorbed radiation. (3) The EMIC study overestimates deforestation since they assumed potential vegetation in the year AD 1000 (Figure S1a). As a consequence of these and other factors, our results show temperature changes that are smaller and regionally and seasonally more offsetting than simulated in the EMIC studies.

[17] Though different from EMIC results, the weak global biogeophysical response found here is supported by previous GCM studies: The global and annual mean cooling found in

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2010GL043010.

Table 2. Results for Global Mean Values From This Study and Previous Studies for Comparison[a]

Simulation	Global	*Brovkin et al.* [2004]	*Matthews et al.* [2004]
LC_{Ph}	−0.03	−0.26	−0.16
LC_{Ch}	0.18 (0.16)	0.18	0.30
LC	0.15 (0.13)	−0.05	0.15

[a] Values in brackets indicate results from the simulation with high land cover dynamics.

the GCM study by *Betts* [2001] for ALCC until today is −0.02 K, and regional effects largely cancel each other on the global mean also in the GCM study by *Bounoua et al.* [2002] and *Findell et al.* [2007]. In a model-intercomparison study, the same model as used here exhibited a climate response to ALCC at the lower end of sensitivity, but within the range of other GCMs [*Pitman et al.*, 2009]. Teleconnections however, which weaken the global signal in our study, were found to be highly model-dependent. Future model intercomparisons should incorporate the biogeochemical response to show the relative strength of the two mechanisms across a range of biogeophysical responses.

[18] A novel aspect of our study compared to the two previous EMIC studies is the assessment of significance over natural variability. Unlike on atmospheric CO_2 [*Pongratz et al.*, 2009b] an early human impact on global temperature cannot be detected (Figure 1a). Even for the localized biogeophysical effects and regions showing significant 20th century cooling such as Europe and Southeast Asia, the preindustrial signal is not significant (Figure 1b and 1c). The regions of strong preindustrial deforestation happen to coincide with high natural climate variability, which conceals in these regions any earlier temperature signal from ALCC. Similarly, no significant biogeophysical cooling for more than single decades is found for the Northern Hemisphere mean temperature (not shown), with a 20th century cooling of −0.03 K. Since the biogeochemical aspects of ALCC are only related to warming, there is no indication that ALCC has substantially contributed to the long-term Northern Hemisphere cooling and "Little Ice Age" found in temperature reconstructions. A similar conclusion has been drawn by *Pongratz et al.* [2009a] based on estimates of radiative forcing from surface albedo changes only, and is confirmed here by the coupled model response. It contradicts therefore previous EMIC and GCM equilibrium studies that attributed the hemispheric cooling to a substantial part to ALCC [*Govindasamy et al.*, 2001; *Bauer et al.*, 2003; *Brovkin et al.*, 2006].

[19] A simplification in our study has been to derive the biogeochemical response as the residual of a fully-coupled simulation and one allowing only biogeophysical mechanisms, instead of simulating it independently. Therefore, the effect identified as contribution from biogeochemical mechanisms may also include synergies. However, considering that the biogeophysical effects are much smaller than the biogeochemical ones, synergies between the two are not expected to be substantial, and have also not been found to be large in the EMIC studies. We further note that we restrict the biogeochemical effects to CO_2 fluxes only and do not consider nutrient limitation; in particular nitrogen limitation is expected to reduce future terrestrial CO_2 uptake, but the reduction is estimated to amount to only 15% for the industrial era [*Zaehle et al.*, 2010] and is likely well below that under the slow CO_2 increase of only 20 ppm in our study.

5. Conclusion

[20] This study has separated the climate response caused by biogeophysical effects of historical anthropogenic land cover change (ALCC) from that caused by biogeochemical effects. It has gone beyond previous studies by applying a high-detail land cover reconstruction, and by performing millennium-scale transient simulations with a coupled atmosphere/ocean GCM. It has found that the biogeochemical warming, caused by CO_2 emissions, is stronger than the cooling caused by biogeophysical effects such as increased albedo. This dominance of the biogeochemical effects has been identified for global mean temperatures, but also for most regions. Only in few regions, such as India or Europe, is the biogeochemical warming substantially weakened by the counteracting biogeophysical response.

[21] We have presented the first GCM study that separates biogeophysical from biogeochemical effects. As computational power, needed for millennium-scale carbon cycle simulations, becomes available, this study should be repeated across a range of GCMs. In particular with respect to a substantial spread of the biogeophysical climate response such a model intercomparison is needed before the sign of the climate response to historical ALCC can be finally agreed on.

[22] **Acknowledgments.** We thank Victor Brovkin for providing the EMIC intercomparison data.

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