GEOPHYSICAL RESEARCH LETTERS, VOL. 36, L02709, doi:10.1029/2008GL036394, 2009

Radiative forcing from anthropogenic land cover change since A.D. 800

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Received 22 October 2008; revised 9 December 2008; accepted 16 December 2008; published 30 January 2009.

[1] We calculate the radiative forcing (RF) from surface albedo changes over the last millennium applying a recently published, population-based reconstruction of anthropogenic land cover change (ALCC). This study thus allows for the first time to assess anthropogenic effects on climate during the pre-industrial era at high spatial and temporal detail. We find that the RF is small throughout the pre-industrial period on the global scale (negative with a magnitude less than 0.05 W/m^2) and not strong enough to explain the cooling reconstructed from climate proxies between A.D. 1000 and 1900. For the regional scale, however, our results suggest an early anthropogenic impact on climate: Already in A.D. 800, the surface energy balance was altered by ALCC at a strength comparable to present-day greenhouse gas forcing, e.g., −2.0 W/m^2 are derived for parts of India for that time. Several other regions exhibit a distinct variability of RF as a result of major epidemics and warfare, with RF changes in the order of 0.1 W/m^2 within just one century. **Citation:** Pongratz, J., T. Raddatz, C. H. Reick, M. Esch, and M. Claussen (2009), Radiative forcing from anthropogenic land cover change since A.D. 800, *Geophys. Res. Lett.*, *36*, L02709, doi:10.1029/2008GL036394.

1. Introduction

[2] Anthropogenic land cover change (ALCC) represents one of the most substantial human impacts on the Earth system. The large-scale transformation of natural ecosystems to managed areas alters climate through several pathways: First, biogeochemical cycles are severely disturbed; e.g., ALCC caused about 35% of the anthropogenic CO_2 emissions during the last 150 years [*Houghton*, 2003]. Second, climate is directly influenced by the modification of the physical properties of the land surface such as albedo, roughness, and evapotranspiration. Modeling studies suggest that through these biogeophysical effects ALCC at mid- and high latitudes induces a cooling [e.g., *Bonan et al.*, 1992; *Claussen et al.*, 2001; *Bounoua et al.*, 2002]. This is explained by the increase of albedo associated with deforestation, which is caused by the snow masking effect of forest as well as by the higher snow-free albedo of non-forest vegetation. With the strong hydrological cycle in the tropics the reduction of roughness, leaf area, and rooting depth by deforestation reduces the evapotranspiration stronger than in the extra-tropics. The loss of evaporative cooling may thus compensate the albedo effect in the tropics so that ALCC can even lead to a local warming [e.g., *Claussen et al.*, 2001; *Bounoua et al.*, 2002; *DeFries et al.*, 2002]. On the global scale, the opposing biogeophysical effects of ALCC widely cancel each other, but regional climate is significantly influenced by ALCC and may even affect remote areas via teleconnections [e.g., *Chase et al.*, 2000].

[3] While ALCC has been recognized as a key factor for present climate change, its role for historical climate is less clear. Concerning biogeophysical effects, most studies suggest a global cooling as a result of the albedo changes from the dominating midlatitudinal deforestation. The European "Medieval Warm Period" as well as the long-term cooling during the middle of the last millennium may largely be explained by the land cover changes over this period [*Govindasamy et al.*, 2001; *Goosse et al.*, 2006]. Also *Brovkin et al.* [1999] obtain biogeophysical cooling from historical ALCC, most strongly in the northern mid- and high latitudes. They show that the impact of historical ALCC on climate is of comparable size as concurrent changes of other climate forcings, e.g., solar irradiance and atmospheric CO_2, and is crucial for reproducing historical climate. From these studies we conclude that historical ALCC may have important impacts on regional and possibly global climate through its biogeophysical effects on the atmosphere. However, all previous studies covering the last millennium are based on ad hoc approximations of historical ALCC. In this study, we use a recently published high-resolution reconstruction of ALCC for the last millennium to address the climate impact from historical ALCC at high spatial detail over the course of the history.

[4] For this assessment we apply the radiative forcing (RF) measure, which is calculated as the change in the net shortwave radiation flux at the tropopause after the forcing agent is introduced but prior to any climate feedbacks. In the case of land cover change, the RF is usually determined for the change in surface albedo. Studies have shown that the RF concept is less well applicable to ALCC than to the classic climate forcings such as well-mixed greenhouse gases: First, biogeophysical effects of land cover change other than albedo changes may also impose climate forcings, e.g., changes in evapotranspiration and non-radiative processes [*Pielke et al.*, 2002; *Davin et al.*, 2007]. The albedo effect has, however, been shown to be dominant on global scale [*Betts et al.*, 2007]. Second, the biogeochemical forcing counteracts biogeophysics, with a similar strength on the global mean [*Brovkin et al.*, 2004], but with much less regional heterogeneity. It is, however, usually treated separately from the biogeophysics due to its different nature of processes and impacts and is not

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0094-8276/09/2008GL036394$05.00

Table 1. Comparison of Global Annual Mean Radiative Forcing From Several Studies for ALCC[a]

Study	Present[a] (W/m^2)	Pre-industrial[a] (W/m^2)	Industrial (W/m^2)	Fraction[b] (%)
Betts et al. [2007]	−0.24 (1990)	−0.06 (1750)	−0.18 (1990–1750)	75
Brovkin et al. [2006]	−0.20 (1992)	−0.06 (1700)	−0.14 (1992–1700)	75
this study	−0.21 (1992)	−0.04 (1700)	−0.18 (1992–1700)	83
this study	−0.21 (1992)	−0.05 (1800)	−0.16 (1992–1800)	74

[a]Reference for present and pre-industrial is potential vegetation.
[b]The contribution of the industrial time period relative to the present radiative forcing.

considered in this study. Third, the common application of RF to global mean climate may underestimate the impact of ALCC, as ALCC is a spatially highly heterogeneous perturbation where regional effects often differ in sign, so that they cancel out on global average despite possibly large regional climate impacts. ALCC thus requires a regionally explicit analysis. Nevertheless, the RF concept and its application to albedo changes remain a standard tool to assess the importance of ALCC for climate, and has frequently been applied to quantify the effects of ALCC on climate for the last 300 years [e.g., *Myhre and Myhre*, 2003; *Betts et al.*, 2007]. By applying this measure to the entire last millennium, our study allows to consistently compare pre-industrial effects of ALCC to publications covering the industrial period.

2. Radiative Forcing Calculations

[5] The RF calculations are performed with the land surface scheme JSBACH [*Raddatz et al.*, 2007] coupled to the climate model ECHAM5 [*Roeckner et al.*, 2003] at a horizontal resolution of T63 (equivalent to about 1.8 degree) with 31 vertical levels. Atmospheric greenhouse gas concentrations, sea ice cover, and sea surface temperature are prescribed to present-day conditions. Computation of the surface shortwave radiation budget includes a spatially-explicit surface albedo calculation for the near infrared as well as the visible range. It depends on the albedo of the soil surface [*Rechid et al.*, 2008], snow cover, and the vegetation composition, in particular the albedo of the canopy and the snow masking of forest. Each grid cell comprises fractions of the three agricultural types (crop, C3 pasture, C4 pasture) and 11 natural vegetation types, each with prescribed canopy albedo and interactive phenology. RF is calculated following the method of *Betts et al.* [2007] with potential vegetation cover as reference.

[6] Simulations are performed for every hundredth year between A.D. 800 and 1992, with an additional run for A.D. 1347, with each simulation comprising 11 years with fixed land cover. Of these, 10 years are used for analysis after one year of spinup. For land cover of the respective years and potential vegetation, spatially aggregated maps of the land cover reconstruction by *Pongratz et al.* [2008] are used. This reconstruction is based on published maps of agricultural areas for the last three centuries. For earlier times, a country-based method was applied that uses population data as a proxy for agricultural activity.

3. Results

[7] The model simulations yield a global annual mean RF of −0.21 W/m^2 for present vs. potential vegetation cover and of −0.18 and −0.16 W/m^2 since A.D. 1700 and 1800, respectively, which compares well to the studies summarized by Table 1. Global annual RF is negative and less than 0.04 W/m^2 and 0.05 W/m^2 in magnitude throughout the pre-industrial times A.D. 800 to 1700 and 1800, respectively (Figure 1). Prior to the large-scale deforestation of the tropics, the Northern Hemisphere has always been affected by agricultural expansion more strongly than the Southern Hemisphere. While the latter experienced a steady strengthening of RF, epidemics and warfare lead on the Northern Hemisphere to temporary reduction of the strength of RF.

[8] While the global annual mean RF was only −0.01 W/m^2 in A.D. 800, regional annual values are as low as −2.0 W/m^2. The strongest forcing at the beginning of the last millennium is simulated for the Indian subcontinent and South China, where large agricultural expansion on previously forested area coincides with high insolation throughout the year (Figure 2). Our results show strong forcings also for the more northern parts of China: negative in summer (JJA) and fall (SON), but positive in winter (DJF) and spring (MAM) when the bare agricultural areas expose more of the dark soil than before deforestation, an effect also simulated for the Black Sea region in spring and autumn. High seasonality of RF also occurs in Europe: although the increase in albedo is highest during winter, when the increased masking of the vegetation by snow takes effect in all northern areas, RF is less than half compared to the summer, where changes in canopy albedo are dominating.

[9] The already strong forcing further strengthens in South and Southeast Asia during the last millennium (zonal means in Figure 2), similar to Europe, where agriculture further expands into Central Asia in the 19th and 20th

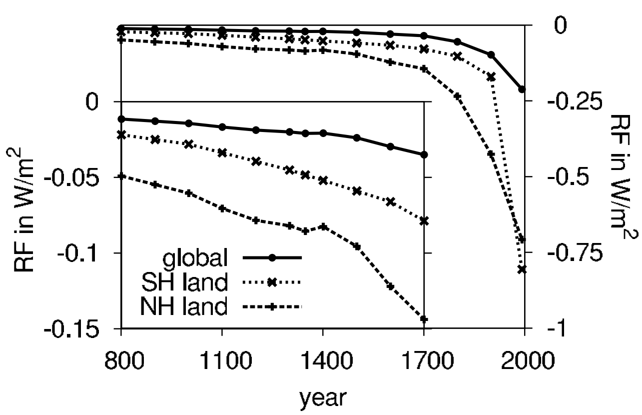

Figure 1. Annual mean radiative forcing (RF) in W/m^2 averaged over the globe, Northern Hemisphere land, and Southern Hemisphere land, respectively, for A.D. 800 to 1700 (inset, left axis) and A.D. 800 to 1992 (right axis).

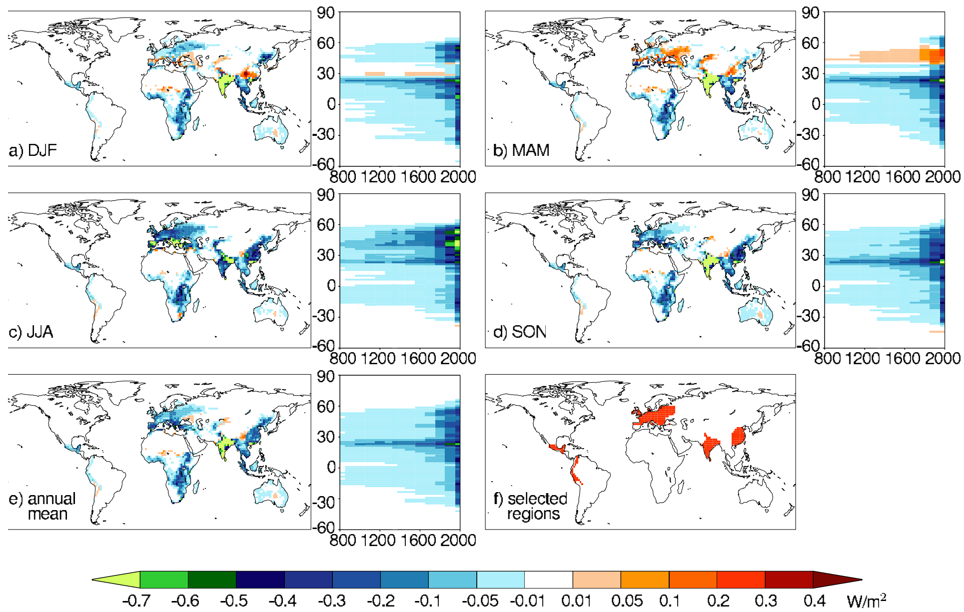

Figure 2. (a–d) Seasonal and (e) annual mean radiative forcing (RF) in W/m^2. (left) Map showing RF for the year A.D. 800; only areas significant at the 95% level are shown. (right) Zonal means of RF for A.D. 800 to 1992. Note the irregular scale around 0 on the color scale. (f) The red areas indicate the regions of Figure 3.

centuries. During the recent centuries the colonization of North America increasingly contributes to the decrease of RF in the Northern Hemisphere midlatitudes during winter, summer, and fall. During spring, agricultural expansion in the northern Great Plains increases the positive zonal RF. RF on the Southern Hemisphere grows as a consequence of the Bantu expansion and subsequent agricultural intensification during pre-industrial times. Since the 18th century European colonization of South America and Australasia further reduce Southern Hemisphere RF. Tropical deforestation strongly decreases RF in the last century.

4. Discussion

[10] The RF from ALCC is small during pre-industrial compared to industrial times (Table 1). The time period 1800–1992 covers 74% and 79% of the changes in global mean RF of the entire agricultural period and of the last thousand years, respectively. The RF from ALCC during industrial times is of the same order of magnitude as solar variability, which amounts to about 0.6 W/m^2 over the last millennium, causing temperature variabilities in the order of 0.2 K [*Crowley*, 2000]. The changes of RF from ALCC during the pre-industrial times of the last millennium are one order of magnitude smaller than solar variability, and two orders in comparison with volcanic forcing, as large eruptions typically cause a RF of several W/m^2 [*Crowley*, 2000]. ALCC, however, differs from the natural forcings in two respects: First, ALCC constitutes a rather permanent forcing, unlike volcanic eruptions. By its persistence over centuries even a small forcing as pre-industrial ALCC may significantly affect the long-term energy balance. This notion has been supported by previous studies attributing Northern Hemisphere cooling to ALCC [e.g., *Govindasamy et al.*, 2001; *Goosse et al.*, 2006] and will be discussed in the following. Second, ALCC constitutes a highly heterogeneous forcing and opposing effects in time and space tend to counterbalance on the global and annual mean so that significant regional effects may be masked. *Betts et al.* [2007], for example, find a cooling of 1–2 K in winter and spring over northern mid-latitude agricultural regions as a consequence of ALCC-induced albedo changes. In this study, annual mean values as low as −2.0 W/m^2 are simulated for South Asia in A.D. 800, which are in the same order of magnitude, though opposite in sign, as the greenhouse gas forcing in present times. Despite small mean values of RF, ALCC may thus have altered regional climate already a thousand years ago. Specific regions further exhibit very distinct histories of agricultural development with partly abrupt changes in RF, as will be illustrated later.

[11] The negative RF in the northern midlatitudes during fall, winter, and most notably summer must be expected to have a cooling effect in accordance with studies by, e.g., *Betts et al.* [2007]. This albedo change has also been suggested by *Govindasamy et al.* [2001] as the key player in explaining the Northern Hemisphere cooling of about 0.25 K between A.D. 1000 and 1900 reconstructed from climate proxies [*Mann and Bradley*, 1999]. In our study, the RF of the Northern Hemisphere decreases by 0.11 W/m^2 during this period, as compared to a RF of 0.28 W/m^2 by *Govindasamy et al.* [2001]. In contrast to their study, our findings thus suggest that ALCC during this time period cannot be the major cause for the cooling. A main difference is that we apply a detailed land cover reconstruction, while *Govindasamy et al.* [2001] assume present-day land cover for the year 1900 and potential vegetation in A.D. 1000 so that deforestation is significantly overestimated.

[12] *Ruddiman* [2007] suggests that epidemics such as the bubonic plague in the 14th century Europe and the mass mortality in the Americas after European arrival had lowered atmospheric CO_2 concentrations, because agricultural land was abandoned in the course of the many

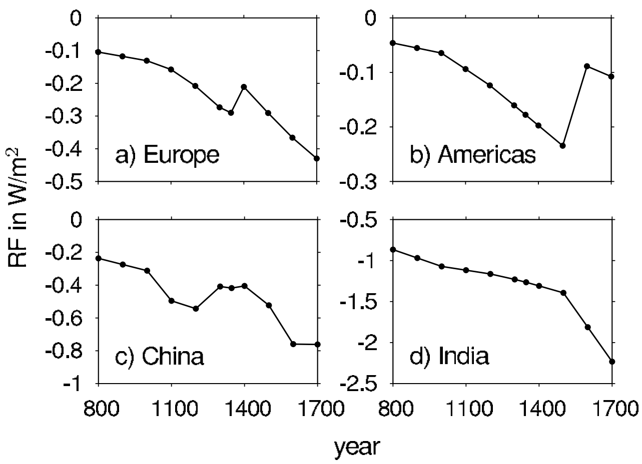

Figure 3. Annual mean radiative forcing (RF) in W/m^2 A.D. 800 to 1700 for the four regions indicated in Figure 2f).

deaths and was regrown by natural vegetation. In Figures 3a and 3b we show the RF in these two regions between A.D. 800 and 1700, indicating the effect of the surface albedo changes associated with the two epidemics. Forest regrows on about 0.18 million km^2 in Europe and weakens the RF by about one third or 0.08 W/m^2 in the indicated area within just one century. In the region of the high cultures of Meso- and South America the RF loses strength from −0.23 to −0.09 W/m^2 between A.D. 1500 and 1600. Similarly, warfare may affect land cover by their impact on population distribution; the Mongol invasion and the upheavals after the fall of the Ming Dynasty bring agricultural expansion and the decrease of RF in China to a halt in the 13th and the 17th century (Figure 3c). India is shown for comparison as a region of strong and steady agricultural expansion (Figure 3d). Although the affected areas may be too small to have caused impacts on global climate, local climate may have been altered significantly. These examples illustrate the importance of using a detailed land cover reconstruction rather than ad hoc interpolation between potential vegetation and land cover maps of the late pre-industrial period, as has been done in previous studies, when assessing the effects of historical ALCC on regional climate.

5. Conclusions

[13] While ALCC does not seem to be the major cause of large-scale climate changes such as the Northern Hemisphere cooling, this study demonstrates that on a regional scale ALCC has imposed a significant radiative forcing on climate already in pre-industrial times. The energy balance has been affected by early agricultural expansion not only in the northern midlatitudes, but even stronger in the northern subtropics. Furthermore, evidence was presented that in order to assess the effects of specific historical events on climate, a land cover reconstruction that captures the regionally distinct evolution of agricultural expansion is needed. This work supports previous studies that have emphasized the spatial heterogeneity of the land cover forcing and the relevance to diverge from the global mean values usually associated with the RF concept [e.g., *Pielke et al.*, 2002] and further stresses the relevance of the seasonal variability. Climate simulations for pre-industrial times will help to quantify the actual climate response to all biogeophysical effects of historical ALCC including feedbacks, and transient simulations over the last millennium should be performed to further include the evolution of land cover CO_2 emissions and their impact on pre-industrial climate.

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