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Contribution of surface roughness to simulations of historical deforestation

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ABSTRACT

Surface roughness which partitions surface net radiation into energy fluxes is a key parameter for estimation of biosphere–atmosphere interactions and climate variability. An earth system model of intermediate complexity (EMIC), MPM-2, is used to derive the impact of surface roughness on climate from simulations of historical land cover change effects. The direct change in surface roughness leads to a global surface warming of 0.08 °C through altering the turbulence in the boundary layer. The regional temperature response to surface roughness associated deforestation is very strong at northern mid-latitudes with a most prominent warming of 0.72 °C around 50°N in the Eurasia continent during summer. They can be explained mainly as direct and indirect consequences of decreases in surface albedo and increases in precipitation in response to deforestation, although there are a few significant changes in precipitation. There is also a prominent warming of 0.25 °C around 40°N in the North American continent. This study indicates that land surface roughness plays a significant role which is comparable with the whole land conversion effect in climate change. Therefore, further investigation of roughness–climate relationship is needed to incorporate these aspects.

1. Introduction

Deforestation can affect climate conditions through reducing the roughness of the landscape. Due to its changes in the efficiency of energy transport near the earth's surface, surface roughness is a key parameter used to estimate climate change in response to deforestation. Possible impact of deforestation on climate through change in surface roughness is largely unknown. Therefore, this study focuses on the impact of surface roughness in response to historical deforestation.

Numerous studies have demonstrated the importance of the surface roughness and simulated them. Increases in surface roughness caused an increase in the efficiency with which sensible heat was transferred from the surface to the atmosphere (Rotenberg and Yakir, 2010; Lee et al., 2011; Liu and Chao, 2009). Sud and Smith (1985a) showed that the circulation and rainfall over and adjacent to the Sahara Desert were sensitive to the roughness of the desert surface. In another study, Sud and Smith (1985b) found that the local surface roughness had a large influence on the summer rainfall over India, and that this influence was as important as that of the surface albedo. It was demonstrated that when the roughness length of modeled tropical forests was decreased, the sensible and latent heat fluxes from the forest were reduced, and soil temperatures were increased (Wilson et al., 1987; Dickinson and Henderson-Sellers, 1988). Klink (1992) also found that changes in surface roughness contributed to localized circulation patterns that, in some cases, enhanced the influences of the vegetation discontinuity; in other cases, the circulation served to diminish the effects of surface heterogeneity. Hoffmann and Jackson (2000) obtained that reductions in surface roughness length could also reduce precipitation and influence larger-scale circulation patterns. Therefore, it is necessary to conduct further study on surface roughness.

Indications that deforestation can affect global or regional climate through surface roughness have been gained from many studies using climate models (Davin and Noblet-Ducoudré, 2010). Reduced roughness can decrease the moisture flux convergence as it weakens the boundary-layer convergence into the continental surface-pressure low. It also dominates the reduction in evaporation and the associated temperature increase in response to Amazon deforestation (Lean and Warrilow, 1989). The reduced surface roughness caused a rise in surface temperature by a smaller amount (Lean et al., 1996). Using a fully coupled land–ocean–atmosphere General Circulation Model (GCM), Davin and Noblet-Ducoudré (2010) simulated a global surface warming of

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0.29 K caused by decreases in surface roughness in response to forest removal. However, most of these studies focus on the overall effects of historical deforestation. The relative importance of the surface roughness in response to deforestation is far less certain.

In addition, most of the previous deforestation experiments have been performed using Atmospheric General Circulation Models (AGCMs) without interactive ocean models, while the climate changes induced by deforestation are affected by feedbacks from sea surface temperature and sea ice, including the thermohaline circulation of the ocean (Renssen et al., 2003). The spread of atmospheric temperature over the ocean suggests that the ocean anomaly could be generated by the atmospheric impact of deforestation over Amazonia (Voldoire and Royer, 2005). The surface roughness is used to determine exchange coefficients for momentum, sensible and latent heat fluxes which drives the upper ocean, resulting in sea-surface cooling by passage of a tropical cyclone (Wada et al., 2010). Furthermore, the real climate change is the joint function of Earth system components. So an earth system model is important for simulating the effects of surface roughness on climate.

Given the importance of quantifying the contribution of surface roughness to the historical deforestation effects, and considering the limitation of the present studies, it is appropriate to examine and derive the impacts of surface roughness on the temperature, land surface albedo and precipitation using the McGill Paleoclimate Model-2 (MPM-2) in response to the historical deforestation. Compared to previous millennia, land cover changes (LCC) have notable fluctuations and distinct histories of agriculture are revealed on regional scales during the pre-industrial period. So this paper focuses on the contribution of surface roughness to simulation of historical deforestation since year 1700.

2. Model and experiments

Deforestation, forest were replaced by grassland, decreases the roughness length, which affects the energy and moisture fluxed through altering the drag coefficient and the turbulent flux transfer between the biosphere and the atmosphere, thus climate. We use the MPM-2 (Wang and Mysak, 2000) in which roughness influences the land-surface boundary conditions to analyze such process and obtain the contribution of the roughness to the effects of historical deforestation. As a global climate model, the MPM-2 consists of a 2-D energy and moisture balance atmosphere model and a multi-basin zonally averaged dynamic ocean model based on vorticity conservation. It also includes a dynamic ice sheet model and a zero-layer thermodynamic-dynamic sea-ice model without snow and a land surface model. Its surface temperature is predicted using the energy balance equation. The MPM-2 is interactively coupled to the dynamical vegetation continuous description model based on a continuous bioclimatic classification which provides the relative cover of tree, grass and potential desert for each continent and latitude (Brovkin et al., 1997). Furthermore, MPM-2 has successfully simulated changes in the thermohaline circulation state (Wang et al., 2002) and the last glacial inception (Wang and Mysak, 2002). In addition, MPM-2 has also simulated the climate changes on thousand year scale, such as temperature, precipitation and vegetation distribution (Wang and Yan, 2013).

For historical land cover changes the fractional grassland data set of Pongratz et al. (2008) for the years 1700–2000 is employed. The reconstruction merges published maps of agriculture from AD 1700 to 1992. Most previous studies that included pasture interpreted the expansion of pasture as deforestation or reduced all natural vegetation equally, not taking into account that humans used natural grasslands for pastures rather than clearing forested area in history (Houghton, 1999), thus overestimating LCC. The LCC reconstruction applied here implemented the preferential allocation of pasture on natural grasslands (Pongratz et al., 2009a). Three human use types (crop, C3 and C4 pasture) and 11 natural vegetation types are included in this dataset in global coverage at 30 min resolution. For each year, a map that contains 14 fields is provided. Each field holds the fraction the respective vegetation type covers in the total grid cell (0–1). Its 30' resolution of the dataset is aggregated to the coarse spatial resolution of the model. As for one grid cell, the grass fraction is the sum of crop, grass and pasture fraction, the sum of the remaining vegetation is forest fraction and the remaining fraction of the grid is the desert. In Fig. 1 (top) the scenario is shown in terms of zonally averaged change in grassland fraction. The Northern hemisphere (NH) extratropics experienced rapid grassland expansion between year 1900 and 2000. The time slice for the first year (1700) and final year (2000) are shown in Fig. 1 (bottom) which illustrates that grassland expansion are prominent, especially over Eurasia.

Two experiments are performed with the MPM-2. In the first experiment (referred to as DE) the historical land cover changes are prescribed. The second experiment (referred to as CONTROL) has the same setup as simulation DE except for the exclusion of surface roughness consideration. The surface roughness effect is isolated by subtracting CONTROL from DE. All simulations were run from year 1700 to 2000 with constant greenhouse gas concentrations fixed at pre-industrial values. Earth orbital parameters were kept constant at present-day values. In order to obtain the same initial conditions, we integrate our simulation from year 1700 to 2000 after a spin-up time of 5300 years to equilibrium. In the simulation, atmospheric, oceanic and sea-ice components of EMICs are interactive. The last 30 years' results of the simulation are averaged to analyze the global temperature, albedo and precipitation change. In order to separate the signal of surface roughness effects from the model inherent noise, the statistical significance of the changes was determined using the classic Student's *t* test at a 95% confidence level to compare 30-year climatologies at each model grid cell (Feddema et al., 2005; van der Molen et al., 2011). Grid cells with non-significant changes were removed from the map. When changes are statistically significant at this level, it means the model-simulated changes are more than twice as large as model's internal variation. They serve as a reason for attributing the statistically significant changes of surface climate to the model climate response to land surface roughness alteration rather than the model internal variability (Zhang et al., 2001; Bounoua et al., 2002).

3. Results

The surface roughness has a direct link with the climate system by influencing the degree of coupling between the land surface and the atmosphere, thereby modulating land surface energy fluxes (Xue et al., 1996; Pitman, 2003). Possible impact of historical deforestation on climate through change in surface roughness is largely uncertain. Clearing forests for cropland or pastureland reduces surface roughness and thus reduces the mechanical turbulence and sensible and latent heat fluxes in the boundary layer. In order to reveal the effects of surface roughness quantitatively, the dynamics of global temperature, albedo and precipitation are estimated. Thereby the contribution of surface roughness to climate change in shaping the global and local impact of historical deforestation can be determined. The results that are statistically significant at a 95% level are shown.

The land surface roughness change in response to historical deforestation and the associated albedo change cause a change in the radiation balance of the Earth, with a consequent change in temperature. Fig. 2 (left) displays the patterns of changes in