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Abstract

There are two competing effects of global land cover change on climate: an albedo effect which leads to heating when changing from grass/croplands to forest, and an evapotranspiration effect which tends to produce cooling. It is not clear which effect would dominate in a global land cover change scenario. We have performed coupled land/ocean/atmosphere simulations of global land cover change using the NCAR CAM3 atmospheric general circulation model. We find that replacement of current vegetation by trees on a global basis would lead to a global annual mean warming of 1.6 C, nearly 75% of the warming produced under a doubled CO_2 concentration, while global replacement by grasslands would result in a cooling of 0.4 C. These results suggest that more research is necessary before forest carbon storage should be deployed as a mitigation strategy for global warming. In particular, high latitude forests probably have a net warming effect on the Earth's climate.

Introduction

Previous studies of the effects of land cover change (Betts, 2000; Bonan, 2001; Govindasamy, 2001; Hansen *et al.,* 1997; Brovkin *et al.,* 1999; Bonan, 1997; Oleson *et* *al.,* 2004) have indicated that direct historical mid-latitude land cover change has increased surface albedo, leading to cooling. These studies suggested that human-induced land cover change from forest to croplands could lead to a cooling of 0.25 C on a global basis (Govindasamy *et al*., 2001), which may have contributed to the millennial cooling before the 20th century, and that northern mid-latitude agricultural regions are ~1—2 C cooler in the winter and spring compared to the pre-industrial state due to replacement of forest by croplands (Betts and Falloon, 2005).

Studies of tropical deforestation are inconclusive on its effects on local or global climate. Deforestation has been found to warm the Amazon basin (Costa and Foley, 2000), and in central Argentina the effect of vegetation cover is to lower the surface temperature due to increased evapotranspiration (Nosetto *et al.,* 2005). However several authors (Chen *et al.,* 2001; Snyder *et al.,* 2004; 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.

Studies investigating the question of global effects of extreme land cover change (from a "desert" planet to a maximally forested one; Kleidon *et al.,* 2000; Fraedrick *et al.,* 1999) found an overall cooling effect due to increased evapotranspiration in the forested scenario. However, these models used prescribed sea surface temperatures (SSTs), which constrained the effects of land cover change on global temperature.

To investigate the potential of land cover change to affect the global climate system without the constraint of specified sea surface temperatures, we have simulated the effects of extreme land cover changes using the Community Land Model (CLM) and the Community Atmosphere Model (CAM), coupled to a slab ocean model. Our goal here is not to reproduce the observed pattern of land cover change, nor to realistically simulate possible scenarios for land cover change, but rather to bracket the magnitude of temperature change that is possible in the climate system due to changes in land cover.

Offline Land Model Simulations

To investigate the effects of land cover change, we performed simulations with and without atmospheric feedbacks. For simulations without atmospheric feedbacks, we used the Community Land Model (CLM) in its offline mode (with prescribed atmospheric climatologies). We used version 3.0 of the CLM (Vertenstein *et al.,* 2004), which allows for 15 types of vegetation, as well as bare ground, lake, and glacier. Up to four vegetation types are allowed per grid cell. Each vegetation type has its own leaf and stem area, root distribution, optical properties, and canopy top and bottom heights (Bonan *et al.,* 2002).

To investigate the effects of changes in vegetation in this model, we replaced the standard vegetation type map used by CLM3.0 with maps containing only a single vegetation type in 100% of the occupied grid cells. This was done without regard to whether specific vegetation types could realistically grow in a given grid cell. The percentages of lake and glacier in each gridcell were not changed from the nominal value. We ran the model in offline mode, repeatedly re-using the monthly climatologies of atmosphere data corresponding to the year1998 from the NCEP/NCAR reanalysis dataset[1] for 20 years of simulated time. We then discarded the first five years of the simulation, and averaged the last 15 years. We also performed a 20-year control run using the standard vegetation type map supplied with the CLM3.0 distribution.

We find that the range of responses (2-meter temperature difference from the bare ground simulation over all the different vegetation types) clearly varies depending on latitude, with the strongest responses occurring in the northern region currently occupied by boreal forest. In general, any type of vegetation causes cooling (warming) in low (high) latitudes in comparison to bare ground. Surface albedo change provides the dominant influence in middle and high latitudes (Betts, 2000; Govindasamy *et al.,* 2001), with vegetation producing net warming, whereas in the tropics the main effect is via

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[1] *NCEP Reanalysis data provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, USA, from their Web site at http://www.cdc.noaa.gov/*

evapotranspiration with vegetation causing net cooling (Costa and Foley 2000). The partitioning of heating into evapotranspiration is more efficient at low latitudes, partly because of the exponential relationship between temperature and saturation water vapor pressure. A zonally-averaged plot of localized temperature difference from the bare ground simulation (Fig. 1) shows that the 15 vegetation types can be roughly divided into two groups: open canopy (grass, shrubs), and closed canopy (trees). Actual vegetation is more similar, on average, to open canopy ecosystems than to closed canopy ecosystems. Note that Fig. 1 does not imply an actual temperature change; instead the zonal temperature differences are to be interpreted as the temperature tendency produced by a localized change on a scale small enough to produce no effects on the atmosphere. The offline simulations assume that the atmosphere is an infinite heat reservoir; thus the land flux changes cannot alter the atmospheric state. Fig. 1 suggests that when considering a coupled model that includes both land and atmosphere effects, it would suffice to consider only two types of vegetation: forest vs. grass and shrublands.

Coupled Simulations

To consider effects of atmospheric feedbacks, we used Version 3 of the Community Atmosphere Model (CAM3) (Collins *et al. 2*004) developed at the National Center for Atmospheric Research. We used the finite volume (FV) method for the horizontal dynamical representation of the prognostic variables. The spatial resolution is 2.0° in latitude and 2.5° in longitude, and the model has 26 levels in the vertical. An important aspect of CAM3 is that it has very little systematic bias in the top-of-atmosphere and surface energy budgets. We coupled the CAM3 atmosphere to NCAR's simple slab ocean—thermodynamic sea ice model, which allows for interaction between ocean and sea ice components. The slab ocean model employs a spatially and temporally prescribed horizontal ocean heat transport and mixed layer-depth, which ensures replication of realistic sea surface temperatures and ice distributions for the present climate.

To achieve equilibrium between land, the slab-ocean, and atmosphere, we ran the coupled models for a total of 50 years, allowing 20 years for spinup and averaging the last 30 years of data for analysis. We made control runs with both the current vegetation and with no vegetation (bare soil). Based on the results from our offline runs, we ran two vegetated models, one with trees and the other with grass/shrubs. For the tree run, the vegetation type was specified in latitude bands, with each latitude assigned the most common type of tree at that latitude (based on current vegetation). A similar procedure was followed for the grass/shrub simulation. When no trees were present at a particular latitude (near the poles), current vegetation was assumed.

Figure 2 shows the zonal mean 2-meter air temperature change predicted for the grass, tree, and current vegetation simulations compared to bare soil. For the tree simulation, the overall effect is an increase of 1.6 C globally (2.3 C for the land only). Results from the grass/shrub simulation indicate that the overall influence of grass vs. bare soil is cooling. The amount of cooling is small, 0.03 C globally (0.1 C for the land only). The current vegetation simulation is 0.35 C warmer on a global basis than the bare ground simulation, mainly due to the presence of boreal trees. Thus according to this model the replacement of current vegetation by trees at all latitudes would produce an average warming of 1.3 C globally, and 1.9 C over land, and the replacement of current vegetation by grassland would result in a global cooling of 0.38 C, or 0.49 C over land.

Figure 3a shows a map of the temperature difference between the tree simulation and the bare soil simulation. Note that the heating effect of forest, which is confined to latitudes of $> 50^{\circ}$ in the offline runs, now extends down to 10-15° N. The albedo-change effect dominates over the evapotranspiration effect from the poles to the tropics in this case, due to feedback between the atmosphere and the land surface. It is also clear from Fig. 3a that there are "downwind" heating and cooling effects from the land to the oceans.

Discussion

After 50 years, when the model simulations have reached equilibrium, the difference between the net shortwave flux for the tree and bare ground simulations is 3.17 W/m^2.

We have calculated the climate sensitivity of the model from a 50-year doubled CO_2 scenario as 2.2 C, with a radiative forcing of 3.5 W/m^2. This would imply an equilibrium difference of 2 C degrees for a net shortwave flux of 3.17 W/m^2. The model simulated warming between the tree and bare ground scenarios is 1.6 C, in reasonable agreement with the expected value.

The warming effect due to the presence of trees clearly originates from the effect of trees on the surface albedo (Fig. 3b). In the bare ground simulation, the average land albedo is 0.23 for both the offline and the coupled model simulations. It decreases to 0.17 and 0.15 in the offline and coupled cases respectively. The larger decrease in albedo in the coupled simulation is due to a decrease in snow cover—the annual average snowfall decreases 20% at 45-90^o N latitude in the tree simulation compared to the bare ground simulation. The decrease in snow leads to a decrease in surface albedo, which leads to an increased absorption of solar radiation, which increases the surface temperature, melting more snow. This snow-albedo feedback effect is responsible for about 25% of the change in ground albedo between the bare ground and tree models in the coupled model (Fig. 3b). It is clear that the maximum surface albedo change occurs in northern areas where snowfall has decreased due to the increase in temperature.

A previous study (Kleidon *et al.,* 2000) has investigated the effects of a change from a desert world to a green planet in the ECHAM4 general circulation model with fixed sea surface temperatures. In contrast to our results, this model produced a net global land temperature change of -1.2 C, and a global change (including oceans) of -0.3 C. This cooling is due to increased evapotranspiration under the tree scenario. Models using prescribed SSTs do not allow feedbacks between the land and oceans; any increase in land temperature is constrained by the effects of the infinite heat reservoir of the oceans. Our model, in contrast, allows the ocean temperatures to change, and this allows a better representation of the feedbacks between the land surface and oceans.

In terms of the absolute potential for temperature modification by land cover change, there appears to be much more potential for heating by reforestation (planting new trees) than cooling by carbon storage. This has important policy implications, since incentives for tree plantations in non-equatorial regions may produce the opposite effect to that desired. A previous study (Betts 2000) has found that the albedo-change-induced warming due to boreal reforestation could be comparable and opposite to the carbon storage effects of cooling. Since the magnitude of temperature change found here is close to that predicted due to carbon-storage effects, a fully coupled model including dynamic vegetation would be useful to more closely investigate which effect is likely to dominate.

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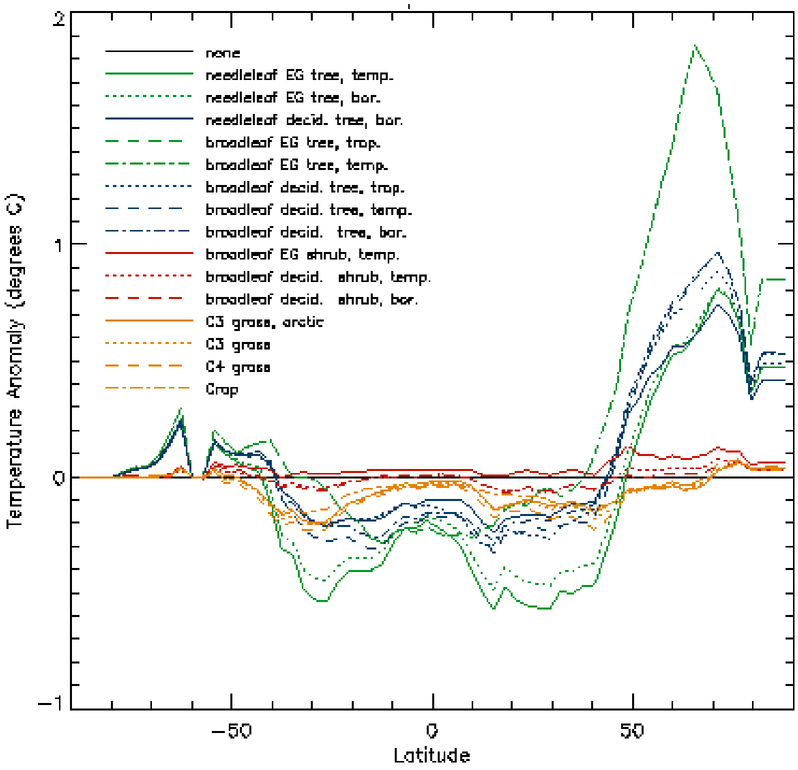

Fig. 1: The zonal average 2-meter atmospheric temperature difference between different vegetation types and bare ground for a localized small-scale change in vegetation that does not affect the atmosphere.

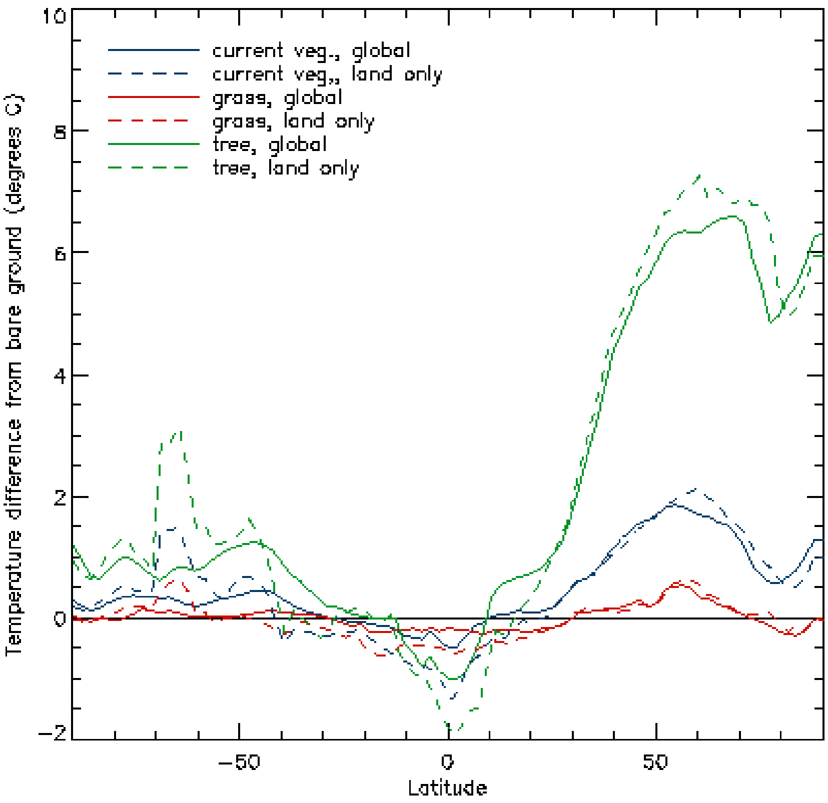

Fig. 2 Annual average zonal change in 2-meter air temperature (model minus bare ground) for different scenarios in the coupled atmosphere-land-slab ocean model. Solid lines indicate averages over the whole earth's surface; dashed lines are averages over land only. Average temperature anomalies from bare ground are: current vegetation, global: +0.35; current vegetation, land only: +0.39. Grass, global: -0.03; grass, land only: -0.10. Tree, global: +1.6; tree, land only: +2.3.

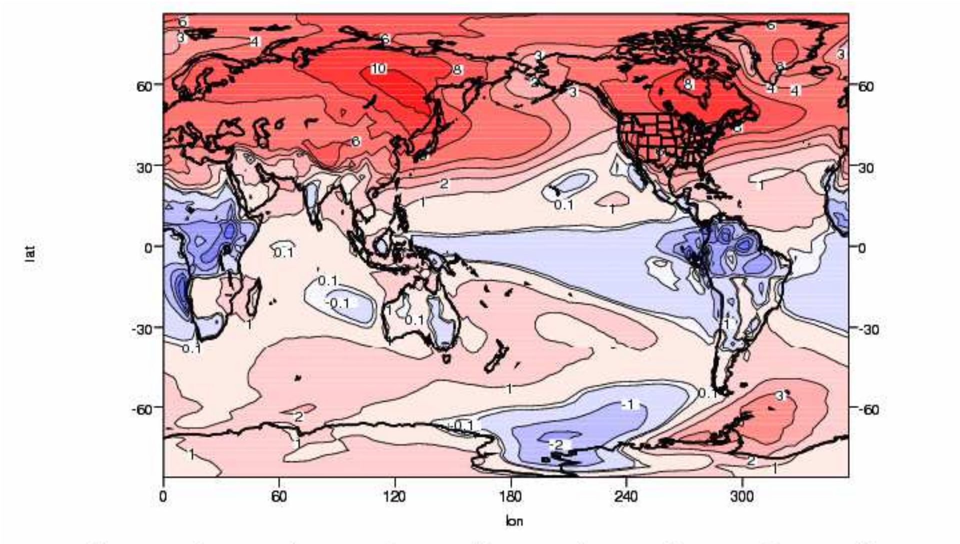

Fig. 3a. Change in annual average 2-meter temperature in degrees C for the tree simulation minus the bare ground simulation. Note the "downwind" heating and cooling effects from the land to the slab ocean.

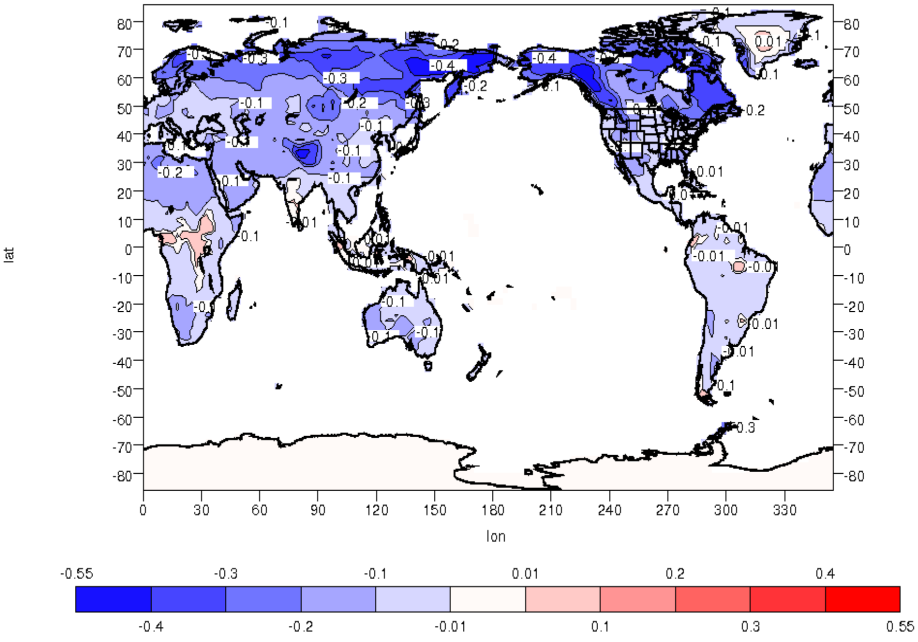

Fig.3b Change in annual average surface albedo for the tree simulation minus the bare ground simulation.