Anthropogenic land cover changes in a GCM with surface albedo changes based on MODIS data

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ABSTRACT: This study uses a global climate model (GCM) to investigate the climate response at the surface and in the atmosphere caused by land use change. The climate simulations are performed with the National Center for Atmospheric Research Community Land Model 3.5 (CLM3.5) coupled to the Community Atmosphere Model 3 (CAM3) and a slab ocean model. We use the Moderate Resolution Imaging Spectroradiometer (MODIS) surface albedo product to represent surface albedo in the CLM3.5 for both present day and to reconstruct the surface albedo for natural pre-agriculture conditions. We compare simulations including vegetation changes and surface albedo changes to simulations including only surface albedo changes. We find that the surface albedo change is most dominant in temperate regions while the change in evapotranspiration drives the climate response in the tropics. Our results show that land cover changes contribute to an annual global warming of 0.04 K, but there are large regional differences. In North America and Europe, the surface temperatures decrease by −0.11 and −0.09 K, respectively, while in India the surface temperatures increase by 0.09 K. When we fix the vegetation cover in the simulations and let the climate changes be driven only by the differences in surface albedo, the annual global mean surface warming is reduced, and all three regions are now associated with surface cooling.

We also show that the surface albedo value for cropland is of major importance in climate simulations of land cover change. The surface albedo effect is the main driving mechanism when the change in surface albedo between agricultural and natural vegetation is substantial. Finally, we argue that differences in the surface albedo value of cropland implemented in earlier land use change studies explain the diversity in the sign and magnitude of the climate response. Copyright © 2009 Royal Meteorological Society

KEY WORDS land cover change; surface albedo; water vapour; satellite data; surface temperature; GCM; CLM; MODIS

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1. Introduction

Anthropogenic land cover changes have an impact on climate through changes in surface properties (Forster et al., 2007; Bonan, 2008). Europe, South Asia and North America have experienced deforestation over large areas, like parts of South America and South Africa (Pongratz et al., 2008; Ramankutty et al., 2008). Earlier studies of land use change show diversity in the surface temperature change. Some studies show that land use change induces a global warming (Zhao et al., 2001; Findell et al., 2007), but they also point at the regional differences when forest has been replaced by crops. Zhao et al. (2001) and Findell et al. (2007) found a small global mean surface temperature increase, 0.01 and 0.008 K, respectively. However, some studies show a global mean cooling, e.g. Betts (Betts, 2001; Betts et al., 2007), who calculated a decrease of 0.06 K over land due to deforestation. Hansen et al. (2005) estimated a global ensemble mean surface temperature change of −0.04 ± 0.02 K including five ensemble members. These two studies have a strong cooling in mid-latitudes and they suggest that the surface albedo change effect is the dominant biogeophysical force of land use change on climate, rather than the change in evapotranspiration, which is the driving mechanism that causes a surface warming in the tropics (Bounoua et al., 2002; DeFries et al., 2002; Bonan, 2008). Climate simulations of land use change are expected to be sensitive to the surface albedo value of cropland (Myhre and Myhre, 2003), and this may explain the diversity in the results among the studies mentioned above. The fact that the different mechanisms contribute to temperature and evaporation changes of opposite signs give land cover changes an uncertain role in the contribution to current climate change.

By changing the vegetation from forest to crops, the biogeophysical properties of the surface are modified. The surface albedo is altered and the roughness length, rooting depth and leaf/stem area index (LAI/SAI) are reduced. There are some regions covered with grassland or sparse vegetation, such as barren land and desert,
which also have been modified for land use purposes. These regions are associated with decreased surface albedo and increased roughness length, rooting depth and LAI/SAI.

Surface albedo is the ratio between reflected and incident solar radiation at the surface. When surface albedo increases, less solar radiation is absorbed by the surface and the result is a surface cooling. The decrease in roughness length leads to a decrease in boundary layer mixing and therefore less latent and sensible heat fluxes away from the surface and a subsequent surface warming. When the rooting depth is reduced, less soil water is available for evapotranspiration and may cause increased runoff. Stomatal resistance controls the transpiration of water vapour through the canopy. The resistance is different in cropped plants compared to trees and accordingly changes the mass flow of water through the leaves. LAI and SAI are an estimate of the vegetation density and controls the amount of sunlight through the canopy. It is also a parameter that controls the photosynthesis and the canopy resistance to evapotranspiration.

Globally, all land cover conversions would potentially impact the water flow through the canopy and can either increase or reduce available water vapour in the atmosphere. Deforestation is alleged to have decreased water vapour flow from the land surface to the atmosphere by 4%, an amount which is almost compensated for by the increased evaporation due to irrigation (Gordon et al., 2005). Water vapour has a key role in our climate system, i.e. through evaporation from the surface and in formation of clouds and precipitation, and probably causes a strong positive climate feedback mechanism. Enhanced or reduced water vapour in the atmosphere due to land use change is not a direct feedback from anthropogenic activity; instead, humans change the water cycle indirectly because of the change in evapotranspiration through the vegetation and evaporation from the soil. The only way by which human activity directly affects the water cycle is through watering crops, i.e. irrigation (Boucher et al., 2004), but this is beyond the scope of this paper.

The main focus in this study is to look at responses to land cover change in a global climate model (GCM) through changes in (i) temperature, (ii) surface fluxes (latent and sensible heat) and hydrology, (iii) clouds and precipitation and (iv) water vapour in the atmosphere. We also look further into the difference in climate response between the phenology changes and the surface albedo change associated with land use.

2. Method

This section describes the modelling tool used for the climate simulations and includes a description of the vegetation data sets for present and pre-agricultural times. Because we focus separately on the surface albedo change, the reconstruction of the surface albedo data set for pre-agricultural time is described in more detail. Finally, we describe the different climate simulations and represent the four cases included in the experimental set-up.

2.1. The Global Climate Model

The climate simulations are performed with the National Center for Atmospheric Research (NCAR) Community Land Model 3.5 (CLM3.5) coupled to the Community Atmosphere Model 3 (CAM3) (Collins et al., 2006) and a slab ocean model (Kiehl et al., 2006). The land model is an upgraded version of the CLM3 (Dickinson et al., 2006), where the most important modification for this purpose is an improved hydrology cycle (Oleson et al., 2008). All simulations are averaged over the last 30 years of a 40-year integration. The atmospheric CO₂ concentration is set to present day and there are no feedback mechanisms due to changes in the carbon cycle.

We treat the vegetation changes and surface albedo changes in the land model separately. Vegetation changes are relative to the present day vegetation data set in the CLM3.5 and a data set of potential natural vegetation in the absence of agriculture. The surface albedo simulated in CLM3.5 varies with snow cover, soil moisture, leaf and stem optical properties, and LAI/SAI. For these experiments, we altered the model so that simulated albedo during snow-free conditions is replaced by specified albedos derived from the Moderate Resolution Imaging Spectroradiometer (MODIS). The estimated surface albedo change is based on vegetation and surface albedo data sets provided by MODIS. The following sections describe both methods more thoroughly.

2.2. Vegetation data sets

A remotely sensed fractional vegetation cover data set is used as current vegetation in CLM3.5 (Bonan et al., 2002; Oleson et al., 2008). This data set includes seven primary plant functional types (PFTs) (needleleaf evergreen/deciduous tree, broadleaf evergreen/deciduous tree, shrub, grass and crop) and seven variants within the primary types (arctic/boreal/temperate/tropical trees, C3/C4 grasses, and evergreen/deciduous shrubs). Every PFT is associated with biogeophysical parameters to describe the vegetation structure. CLM3.5 operates with a constant vegetation fraction throughout the year, where the LAI/SAI for each PFT describes the seasonal change.

Based on the historical data of global vegetation cover, Ramankutty and Foley (1999) created a data set for the purpose of investigating land cover changes. Considering the same climate as today, they produced a global vegetation data set where anthropogenic vegetation, such as cropland, is replaced by a natural vegetation cover. The cropland PFT in the current day vegetation data set in CLM3.5 is replaced with the correspondent PFT from the data set of Ramankutty and Foley (1999). The pre-agricultural data set provided by Ramankutty and Foley (1999) includes biomes (a set of PFTs), and not all biomes correspond with the PFTs used in the CLM3.5. If the biome does not have a corresponding PFT in CLM3.5
2.3. Surface albedo change based on MODIS satellite data

MODIS surface albedos from the MODIS 16-day surface albedo product MOD43C1 (v004) (Schaaf et al., 2002), for years 2001–2006, are averaged into a monthly snow-free surface albedo data set to use as input for the present day surface albedo in the climate land model (albedomodis). A pre-agricultural global surface albedo map (albedonatural) is derived based on (1) MODIS present day surface albedo (albedomodis), (2) the MODIS land cover product (MOD12C1) and (3) the potential natural vegetation data set from Ramankutty and Foley (1999). The MODIS land cover product includes 16 vegetation classes, following the International Geosphere–Biosphere Program (IGBP) classification, with a fractional cover which allows for multiple vegetation classes in each grid cell.

A surface albedo value (alb) is calculated for every vegetation class (i) in the MODIS current day vegetation map. This is done by averaging all grid cells in albedomodis for each class where the vegetation covers more than 95% of the grid cell. A global surface albedo map for present day (albedomodis(pres)) is then computed. The surface albedo value in each grid cell (x, y) is estimated by the MODIS fractional cover of vegetation (frc) and the estimated averaged surface albedo value (Equation (1)). A global surface albedo map for natural vegetation cover (albedonatural) is derived by the same method (Equation (2)) but excluding cropland (i = 12) and cropland mosaic (i = 14). These classes are replaced with a surface albedo value for the natural vegetation defined by Ramankutty and Foley (1999). We increase the fraction of natural vegetation in a grid cell by the same portion as the cropland fraction that has been replaced.

\[
albedo_{\text{natural}}(x,y) = \Sigma_i frc_i \cdot \albedo_i \quad i = 1, 16
\]

\[
albedo_{\text{natural}}(x,y) = \Sigma_i frc_i \cdot \albedo_i \quad i = 1, 16
\]

The estimated change in surface albedo between current and natural vegetation is \(\Delta\albedo\) (Equation (3)). The albedo_natural in Equation (4) is computed subtracting the \(\Delta\albedo\) from the retrieved current surface albedo (albedomodis). This method uses the strength of a satellite-derived surface albedo map for the present day to calculate a surface albedo data set for natural vegetation. To avoid negative values in the calculated albedo_natural (i.e. if the calculated \(\Delta\albedo\) is higher than albedomodis), the albedo_natural is constrained to not have lower values than the global minimum albedo value retrieved by the satellite.

\[
\Delta\albedo = \albedo_{\text{natural}}(\text{pres}) - \albedo_{\text{natural}}(\text{natural})
\]

\[
\albedo_{\text{natural}} = \albedo_{\text{modis}} - \Delta\albedo
\]

As a sensitivity experiment, we artificially set the albedo of cropland to higher values in the present day surface albedo. The calculation of a present surface albedo map including increased surface albedo value for cropland is carried out as in Equation (5), by replacing the fraction of cropland in albedomodis with its new and higher surface albedo value. The new surface albedo value for cropland is 10% in the visible part of the spectrum (VIS), and 30% in the near infrared (NIR) (Equation (6)). As a reference, the averaged surface albedo of cropland from albedomodis is divided into different regions and is given as monthly values and varies between 2 and 8% in VIS and 10 and 26% in NIR.

\[
albedo_{\text{croplandhigher}} = \albedo_{\text{modis}} \cdot (1 - frc_{12,14})
\]

\[
+ \albedo_{\text{vishigh}} \cdot frc_{12,14}
\]

\[
\albedo_{\text{vishigh}} = 10\% \quad (\text{VIS}),
\]

\[
\albedo_{\text{vishigh}} = 30\% \quad (\text{NIR})
\]

The surface albedo from MODIS is provided for direct and diffuse light (BS and WS albedo) and for two bands (VIS and NIR). Table I shows the annual global mean surface albedo for snow-free conditions for the present day as retrieved by MODIS. The annual global mean surface albedo for reconstructed pre-agricultural conditions is also included in the table as well as the surface albedo for the present day with higher value for cropland. The annual global snow-free surface albedo in VIS BS is 4.24% for the present-day conditions. When we introduce the higher value for cropland, the annual global surface albedo for the present day has increased relatively by 8% compared to MODIS (from 4.24 to 4.57%). The annual absolute change in snow-free surface albedo between current and pre-agricultural land cover is shown in Figure 1 and global and regional values are summarized in Table II. The surface albedos for current day and pre-agricultural times are shown in percent (%) in Table I, while the changes in surface albedo are shown in Figure 1 and Table II as the absolute difference between the two conditions (current – pre-agricultural).

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Table I. The annual global mean snow-free surface albedo (%) for current day, pre-agricultural times, and current day with higher cropland values based on MODIS.

<table>
<thead>
<tr>
<th>Surface albedo (%)</th>
<th>Current day</th>
<th>Pre-agricultural times</th>
<th>Current day with higher cropland albedo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visible black sky</td>
<td>4.24</td>
<td>4.15</td>
<td>4.57</td>
</tr>
<tr>
<td>Visible white sky</td>
<td>4.48</td>
<td>4.40</td>
<td>4.80</td>
</tr>
<tr>
<td>Near infra red black sky</td>
<td>11.97</td>
<td>11.80</td>
<td>12.67</td>
</tr>
<tr>
<td>Near infra red white sky</td>
<td>12.77</td>
<td>12.63</td>
<td>13.37</td>
</tr>
</tbody>
</table>

Table II. Annual mean surface albedo changes (current – pre-agricultural) in absolute percent based on MODIS snow-free surface albedo and pre-agricultural vegetation from Ramankutty and Foley (1999).

<table>
<thead>
<tr>
<th>Surface albedo (absolute change)</th>
<th>Global</th>
<th>N-Am</th>
<th>Europe</th>
<th>India</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visible black sky</td>
<td>0.09</td>
<td>0.26</td>
<td>0.65</td>
<td>0.75</td>
</tr>
<tr>
<td>Visible white sky</td>
<td>0.09</td>
<td>0.27</td>
<td>0.63</td>
<td>0.84</td>
</tr>
<tr>
<td>Near infra red black sky</td>
<td>0.17</td>
<td>0.78</td>
<td>0.56</td>
<td>1.20</td>
</tr>
<tr>
<td>Near infra red white sky</td>
<td>0.15</td>
<td>0.78</td>
<td>0.41</td>
<td>1.32</td>
</tr>
</tbody>
</table>


2.4. Experimental design

Table III describes the four model simulations which are performed. Because we have the opportunity to change both the vegetation data set and the surface albedo data set in the model, we can study which portion of the climate responses are caused by the surface albedo changes alone and which is due to the other effects of deforestation. Run I, III and IV are performed with the current vegetation map, but with different sets of surface albedo, i.e. (1) current day surface albedo from MODIS, (2) surface albedo in pre-agricultural times, or (3) as in (1) but the surface albedo value of cropland is increased to 10% in the VIS and 30% in the NIR. Run II includes pre-agricultural vegetation as well as the prescribed surface albedo data set for pre-agricultural times based on MODIS.

Figure 1. The annual mean snow-free albedo (absolute) change (current – pre-agricultural) used in CLM3.5. The albedo difference is shown for two bands [visible (a) - (b) and near infra red (c) - (d)] and direct and diffuse radiation [black sky (a), (c) and white sky (b), (d)].
Table III. The model simulations are performed with different types of input vegetation and surface albedo data sets in the model (present or potential).

<table>
<thead>
<tr>
<th>Simulations</th>
<th>Vegetation data</th>
<th>Surface albedo data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run I</td>
<td>Present</td>
<td>Present</td>
</tr>
<tr>
<td>Run II</td>
<td>Potential</td>
<td>Potential</td>
</tr>
<tr>
<td>Run III</td>
<td>Present</td>
<td>Potential</td>
</tr>
<tr>
<td>Run IV</td>
<td>Present</td>
<td>Present (higher cropland values)</td>
</tr>
</tbody>
</table>

Followed by these four simulations we examine four cases (Table IV): CASE 1 considers vegetation cover changes and surface albedo changes between the present and pre-agricultural times. CASE 2 shows climate changes due solely to surface albedo changes, because the vegetation is kept constant in the two simulations. The surface albedo changes in this case apply only for snow-free grid cells and the model simulates the surface albedo if snow is present based on the parameterization in (Oleson et al., 2004b). CASE 1 and CASE 2 have the same snow-free surface albedo change, but since surface albedo in snow-covered region depends on the vegetation cover, this will differ since CASE 1 includes change in the vegetation cover whereas this is not the situation for CASE 2. CASE 3 is equal to CASE 1, but the cropland value in the current day surface albedo map is set to a higher value as described earlier. CASE 4 is equal to CASE 2, but uses the same surface albedo data set as in CASE 3.

The purpose of a set-up like this is to study three important features in land cover change modelling. First, we study the standard case (CASE 1) that includes all the biogeophysical aspects of land cover change. Second, we focus on the surface albedo effect on global climate by comparing CASE 1 and CASE 2. Third, we would like to quantify the differences between using surface albedo change based on satellite retrievals (CASE 1 and CASE 2) and prescribed surface albedo values for cropland (CASE 3 and CASE 4). The latter comparison illuminates the importance of the surface albedo value of cropland when studying land cover changes in a GCM because it will indicate how sensitive the global response from land use change is to the surface value of cropland.

3. Results and discussion

The results from the four cases are shown as annual means and divided into the categories global, global land, North America, Europe and India. A two-tailed student’s t-test is performed, and we present the results in Tables V and VI at 90% and 95% statistical significance levels. The figures are showing the results at the 95% statistical significance level. We study the climate response from land use through changes in temperature, non-radiative surface fluxes, clouds, precipitation and atmospheric water vapour. The surface temperature discussed in the following section is the near surface air temperature.

3.1. Temperature

The global map of annual surface temperature change for CASE 1 is shown in Figure 2(a), and global and regional values are represented in Table V. The annual global mean temperature change is a small warming for the standard simulation (0.04 K), but smaller over land (0.01 K). The strongest change is the surface cooling in North America of −0.11 K, and the surface temperature over Europe has declined by 0.09 K. A warming is seen

Table V. The annual changes (current – pre-agricultural) in parameters for two cases for global mean, global land, North America (N-Am), Europe, and India.

<table>
<thead>
<tr>
<th></th>
<th>CASE 1</th>
<th>CASE 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Global</td>
<td>Global land</td>
</tr>
<tr>
<td>Surface temperature (K)</td>
<td>0.04</td>
<td>−0.01</td>
</tr>
<tr>
<td>Latent heat (W m(^{-2}))</td>
<td>0.06</td>
<td>−0.12</td>
</tr>
<tr>
<td>Sensible heat (W m(^{-2}))</td>
<td>−0.06</td>
<td>−0.12</td>
</tr>
<tr>
<td>Cloud cover fraction (absolute %)</td>
<td>−0.04</td>
<td>0.10</td>
</tr>
<tr>
<td>Precipitation (mm day(^{-1}))</td>
<td>−0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Water column (kg m(^{-2}))</td>
<td>−0.01</td>
<td>−0.02</td>
</tr>
</tbody>
</table>

Student’s t-tests are performed with 90% (underlined) and 95% (bold) statistical significance levels.
Table VI. The annual change in surface temperatures for CASE 3 and CASE 4 divided into global mean, global land, North America (N-Am), Europe, and India.

<table>
<thead>
<tr>
<th>Surface temperature (K)</th>
<th>CASE 3</th>
<th>CASE 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global</td>
<td>−0.04</td>
<td>−0.06</td>
</tr>
<tr>
<td>Global land</td>
<td>−0.08</td>
<td>−0.10</td>
</tr>
<tr>
<td>N-Am</td>
<td>−0.75</td>
<td>−0.74</td>
</tr>
<tr>
<td>Europe</td>
<td>−0.68</td>
<td>−0.61</td>
</tr>
<tr>
<td>India</td>
<td>−0.23</td>
<td>−0.53</td>
</tr>
</tbody>
</table>
| Student’s $t$-tests are performed with 90% (underline) and 95% (bold) statistical significance level.

in India, where the surface temperature has increased by 0.09 K. Only the change in India is statistically significant at a 95% level.

The regional results are generally consistent with other studies indicating that North America has experienced a surface cooling (Zhao et al., 2001; Oleson et al., 2004a). Bounoua et al. (2002) suggest that vegetation conversions in the tropics and sub-tropics warm the surface, and the surface temperature changes at these latitudes are most influenced by the reduced latent heat flux. DeFries et al. (2002) studied a possible future land cover scenario in 2050 when most land cover conversions occur in the tropics and sub-tropics. Whereas previous land cover change mainly appears to be dominated by a surface cooling in the mid-latitudes, they find that future land cover change in the humid tropics gives a surface warming governed by modified latent and sensible heat fluxes. Our model results correspond with these findings. According to Figure 2(a) and the calculated surface temperature change in India in Table V, conversions in the tropics and sub-tropics are most influenced by changes in latent and sensible heat fluxes which cause the surface warming in these regions. However, the results of the surface temperature change in Europe vary from other studies. The differences are associated with the way we choose to represent the current and pre-agricultural vegetation, and thus surface albedo change, the use of a slab ocean model instead of fixed sea surface temperatures and the limits of the geographical regions.

Figure 2. The annual mean change (current – pre-agricultural) in surface temperature (K) for (a) CASE 1, (b) CASE 2, (c) CASE 3 and (d) CASE 4. The figure is only showing areas of statistical significance at confidence level of 95% using a two-tailed $t$-test.
Figure 2(b) shows the surface temperature change for simulations with changes in the surface albedo, but with the vegetation fixed at current conditions (CASE 2). We find a decrease in the surface temperature in all regions, associated with land cover change, even at lower latitudes, such as in South America and South Asia. The annual global mean surface temperature change is reduced to 0.02 K compared to CASE 1. Annual surface temperature changes are strongest in NH over the continents with cooling up to 0.5 K, but the average temperature change over land is $-0.01$ K. The surface albedo effect cools the surface in more regions in CASE 2 than for CASE 1. Northern America and Europe are associated with surface cooling in both cases. However, the temperature change in parts of Asia (especially India) is of opposite signs in the two experiments. This suggests that changes in vegetation which reduce the evapotranspiration in these regions control the surface temperature change more than the surface albedo effect in our simulations.

Because temperature changes in CASE 2 are solely due to snow-free surface albedo, and CASE 1 in addition includes temperature changes from surface albedo in snow-covered regions and vegetation changes, one might expect large changes in the surface temperature between the two cases. Figure 2(a) and (b) shows that at mid-latitudes with large current cropland areas and regions with snow during the winter, the difference between CASE 1 and CASE 2 is relatively small. This is due to a relatively small snow cover in cropland areas in the NCAR CAM3/CLM3.5 model and smaller than the snow cover used in other studies of land use changes (Myhre et al., 2005). It has also been shown that the snow cover simulated by CLM3.5 is underestimated compared to satellite observations (Niu and Yang, 2007).

Figure 2(c) and (d) shows the annual surface temperature change in CASE 3 and CASE 4, respectively. CASE 3 still includes modified vegetation cover, but the strong cooling over the NH suggests that the change in surface albedo is the dominant mechanism in these simulations. This is further demonstrated in Figure 2(d), where the pattern does not show substantial differences compared to Figure 2(c). Further, the global and regional changes in surface temperature in Table VI show small differences between CASE 3 and CASE 4. The level of significance has now increased for all regions to a 95% confidence level.

Hansen et al. (2005) found a global mean annual surface temperature decrease of $-0.2 \pm 0.2$ K based on five ensemble mean simulations from a climate model. The authors claim that the main driving force of the climate response due to land cover change is the surface albedo effect. Their result has many similarities with CASE 3 in our study, where the surface albedo of cropland is altered compared to the surface albedo value retrieved by MODIS. Betts (Betts, 2001; Betts et al., 2007) also argues that the surface albedo effect is the most dominant effect in land use changes, and calculates a decrease over land of $-0.06$ K. His result is much stronger than the surface warming over land of 0.01 K found using satellite-retrieved surface albedo in CASE 1. Additionally, our results show a cooling over land of $-0.11$ K in CASE 3 which is stronger than the estimate of Betts (Betts, 2001; Betts et al., 2007), but still closer than the estimated surface temperature change in CASE 1.

Over land in the mid-latitudes in NH, land cover changes cause an annual surface cooling in all the four experiments. The annual global mean warming in CASE 1 and CASE 2 of 0.04 and 0.02 K, respectively, is significantly influenced by areas of surface warming not directly made by land use changes in the North Atlantic, over Greenland and northern parts of Alaska. These warm regions are caused by teleconnections and changes in the general circulation which leads to changes in warm air into these regions. They are also associated with a decrease in low clouds and an increase in high clouds. Low clouds most likely cool the surface whereas high clouds usually warm the surface. The warming in high latitudes is less pronounced in the other two cases (CASE 3 and CASE 4) and it is not large enough to offset the NH mid-latitude cooling because the direct effect of land cover change in the mid-latitudes in NH has become more significant.

The atmospheric circulation pattern varies between the cases, and the climate responses due to dynamical changes are, in some areas, of the same order of magnitude as the direct response of the land use changes. Regions not associated with land use also experience surface temperature changes. These changes are closely linked to modified precipitation patterns. Note that the vegetation and surface albedo changes influence the local temperatures differently and that the atmospheric circulation also differs between each case. In Africa, Figure 2(a) and (c) shows a surface warming over the northern parts of the continent. This region has not been subject to any land use change, but the surface warming is a consequence of decreased precipitation with a subsequent reduction in latent heat flux. However, this warming feature is missing in Figure 2(b) and (d), suggesting that the global atmospheric circulation induces different precipitation patterns over the northern parts of Africa when we consider only the surface albedo change.

Changes in the vertical temperature profiles for CASE 1 and CASE 2 are shown in Figure 3(a) and (b). The annual global change in the vertical temperature profile is nearly constant with height at 0.04 K in CASE 1 (Figure 3(a)). However, the various regions included in this study behave differently. All regions contribute to atmospheric cooling, and most strongly close to the surface.

For CASE 2, the annual global temperature change in the atmosphere is a constant warming with height at 0.02 K. All regions experience surface cooling, but are more stable with height and smaller in magnitude compared to CASE 1. The changes in vegetation cover in the first case are causing the varying temperature profile throughout the atmosphere for all regions, whereas the
surface albedo changes in the second case only influence the temperature profiles closest to the surface. Globally, the temperature profiles are very similar between CASE 1 and CASE 2.

While the vertical profiles for annual temperature in Figure 3 show large differences between CASE 1 and CASE 2, Figure 3(c) and (d) shows more agreement between CASE 3 and CASE 4, both globally and in all regions. This suggests that when the surface albedo effect becomes larger, the climate response from the change in vegetation canopy is of small importance. Annual global means and all regions in CASE 3 and CASE 4 contribute to a cooling throughout the troposphere.

3.2. Non-radiative surface fluxes and hydrology

Latent heat flux is the flux of energy resulting from evaporation from the canopy and the ground. Since cropland both transpires and evaporates water less than forest, the direct effect of deforestation is a reduction of latent heat flux through the vegetation. Figure 4(a) shows the annual global change in latent heat flux for CASE 1. In areas with extensive land use, the change in magnitude and even sign of the latent heat flux change vary. While India has experienced a reduction in latent heat flux of $-2.45 \text{ W m}^{-2}$, North America and Europe have an increase in the latent heat flux release from the surface.
by 0.94 and 0.81 W m\(^{-2}\), respectively. This opposite sign of the latent heat flux can be explained by increased precipitation and cloud cover in North America and Europe which controls the amount of surface evaporation more than the direct effect of modified vegetation in these regions. In contrast, precipitation and cloud cover decrease in India. The annual change in the global mean of latent heat flux is an increase of 0.06 W m\(^{-2}\), while global mean over land has been reduced by 0.12 W m\(^{-2}\).

Results from CASE 2 show a few differences compared to CASE 1 (Figure 4(b)). The increased latent heat flux in North America remains, but is now only 0.12 W m\(^{-2}\). Europe and India have a reduced latent heat flux of 0.46 and 0.64 W m\(^{-2}\), respectively. Changes in precipitation are weaker than in CASE 1, which feeds back to affect the latent heat flux. The annual global mean change is now a decrease of 0.01 W m\(^{-2}\), and globally, over land, there has been a reduction of 0.13 W m\(^{-2}\).

To further study the change in surface evaporation, we can investigate several land surface hydrology parameters which are summarized in Table VII as global annual mean values over land. This is only interesting for CASE 1, because the surface albedo effect of CASE 2 has a negligible effect on the surface hydrology. Transpiration and evaporation through the canopy has been reduced by 1215 and 320 km\(^3\) yr\(^{-1}\), respectively, which equals \(-2.8\%\) and \(-1.8\%\). However, the evaporation from the soil has increased by 859 km\(^3\) yr\(^{-1}\) (\(+1.8\%)\). A previous estimate of change in surface water flow caused by deforestation was a decrease of 3000 km\(^3\) yr\(^{-1}\), or 4\% (Gordon et al., 2005). If we do not include the increased evaporation from the ground, our results show half the reduction in surface water flow from deforestation through evapotranspiration from the canopy (1535 km\(^3\) yr\(^{-1}\) or 2.3\%) compared to the previous estimate.

Sensible heat flux change is shown in Figure 5(a) for CASE 1. All regions in Table V are associated with a reduction in sensible heat flux for this case. The annual global mean reduction is \(-0.06\) W m\(^{-2}\) (\(-0.12\) W m\(^{-2}\) over land). The strongest reduction is seen in India (\(-3.15\) W m\(^{-2}\)). The decrease in Europe and India is statistically significant to a 95% level.

The results for changes in sensible heat flux in CASE 2 are weaker in magnitude for all regions compared to CASE 1 and no longer statistically significant at the same level (except India), but the pattern of the changes seen in Figure 5(b) is the same.

### Table VII. Annual global changes over land in surface evapotranspiration parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CASE 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canopy transpiration (km(^3) yr(^{-1}))</td>
<td>–1215 ((-2.8%))</td>
</tr>
<tr>
<td>Evaporation of canopy-intercepted-water (km(^3) yr(^{-1}))</td>
<td>–320 ((-1.8%))</td>
</tr>
<tr>
<td>Ground evaporation (km(^3) yr(^{-1}))</td>
<td>859 (+1.8%)</td>
</tr>
<tr>
<td>Total evapotranspiration from the canopy and ground (km(^3) yr(^{-1}))</td>
<td>–677 ((-0.6%))</td>
</tr>
</tbody>
</table>

3.3. Cloud cover and precipitation

Annual global changes of clouds and precipitation are shown in Figures 6(a) and 7(a) for CASE 1 and Figures 6(b) and 7(b) for CASE 2, respectively. Globally, the changes are very small in both the experiments and not statistically significant (except cloud cover change over Europe in CASE 1). Strongest changes occur over Europe in CASE 1 where fractional cloud cover has increased by 1.30\% (absolute change) and precipitation has increased by 0.06 mm day\(^{-1}\).

It is probable that there has been a shift in the annual intertropical convergence zone (ITCZ) in our simulations of land use change. This is most apparent for the experiments including higher surface albedo values of cropland. The ITCZ in CASE 3 and CASE 4 has shifted southwards towards the warmer hemisphere because surface cooling occurs over major parts of the NH (figures not shown). A similar shift has been observed due to cooling of the NH by scattering aerosols (Rotstayn and Lohmann, 2002; Kristjansson et al., 2005). Our
simulations do not include any changes in atmospheric aerosols; thus, the southward shift in ITCZ is caused solely by the surface cooling due to land cover change in the NH.

### 3.4. Atmospheric water vapour

Water vapour changes in the atmosphere due to land use change have not been investigated as much in earlier studies as changes in evapotranspiration at the surface (Gordon et al., 2005; Findell et al., 2007). Figure 8(a) and (b) shows the vertical profile of the annual mean global water vapour relative change in the atmosphere for CASE 1 and CASE 2 and the same regions as discussed in Table V. While the annual global mean water vapour change in Figure 8(a) for CASE 1 shows practically no modification in the vertical profile, the water vapour content increases at the surface and is then reduced with increasing altitude in the atmosphere for the three regions.

In CASE 2, the atmospheric water vapour shows no annual global mean change (Figure 8(b)). The three regions show smaller changes and are shifted towards zero and are more stable with height. All changes in atmospheric water vapour in CASE 1 and CASE 2 are small (less than 2% increase). Further, the surface albedo effect has also a negligible influence on the water vapour content.

Figure 9(a) and (b) shows the annual (absolute) difference in atmospheric relative humidity for CASE 1 and CASE 2. The pattern of the change in relative humidity in both the experiments follows to a large degree the change in the vertical profile of water vapour content. While the annual global mean shows no increase in relative humidity, all the three regions have increased relative humidity at the surface and decreasing relative humidity with height.

The integrated column of available water vapour in the atmosphere is shown in Figure 10(a) and (b) for CASE 1 and CASE 2. The annual global mean water column change in CASE 1 is $-0.01 \text{ kg m}^{-2}$ ($-0.04\%$), and the surface albedo change (CASE 2) decreases the global water column by $0.03 \text{ kg m}^{-2}$ ($-0.10\%$). Compared to irrigation where the global mean water column is increased by 0.14% (Boucher et al., 2004), these are slightly weaker changes. The differences between CASE
1 and CASE 2 are caused by the influence of the deforested canopy on the global water vapour in the atmosphere, i.e. not the surface albedo effect, which is an increase of 0.02 kg m\(^{-2}\) (0.06%). This very small increase in atmospheric water vapour is most likely associated with the surface warming of 0.02 K that occurs if we consider only the vegetation changes.

4. Summary and conclusions

Simulations with CLM3.5 coupled to CAM3 and a slab ocean model have been performed to study land cover changes in a GCM. We have used the MODIS surface albedo product to represent current surface albedo and to reconstruct a surface albedo data set for pre-agricultural times. This is done for the purpose of imposing a satellite-based surface albedo change from the land cover changes into the climate model. Satellite data represent the best available data on global surface albedo. It gives a better representation of the surface albedo instead of using a single value for each vegetation type.

Globally, our results show a small warming in the first case where both vegetation cover and surface albedo have been changed. However, regionally, the results vary: in the main regions of land use change we find surface warming of India, but North America and Europe have cooler surface temperatures today than had before deforestation.

Additional simulations have been performed to further study the surface albedo effect in land use changes. When we exclude the change in vegetation cover and only take account of the satellite-based surface albedo change in the model, the annual global mean warming is reduced. Further, while the surface temperature change in North America and Europe remains a surface cooling, India, in this case, also experiences reduced surface temperature. There is a caveat to this, especially at mid-latitudes, because the difference between the simulations involves surface albedo change in snow-covered regions in addition to vegetation changes. The surface albedo changes are dependent on snow cover fraction; because snow-covered cropland has much higher surface albedo than snow-covered forest. In the simulations with NCAR CAM3/CLM3.5, the snow cover fraction is small in agricultural areas, especially in regions in Europe and North America, so that the difference between either including both vegetation changes and snow-free surface albedo or only including snow-free surface albedo change is small. Further, studies on land use change should investigate differences in the albedo change and surface
temperature change in relation to snow cover and snow depth.

The changes associated with the replacement of temperate forests with agricultural land are broadly similar in North America and Europe. In both the cases, there is surface cooling, decreased sensible heat, increased latent heat, cloud cover and precipitation. In India where the tropical forests have been replaced by crops, the surface temperature increases, while all other parameters in Table V for CASE 1 are reduced. The difference between CASE 1 and CASE 2 is also greater for India than the other two regions, which suggests that the surface albedo change is most dominant in temperate regions while the change in evapotranspiration drives the climate response in the tropics (Bounoua et al., 2002; DeFries et al., 2002; Bonan, 2008).

Most of the changes in CASE 2 shown in Table V are not statistically significant to a 95% level. This can be explained by the importance of the evapotranspiration from the vegetation canopy and also that the satellite-based surface albedo changes due to land cover change are not large enough to produce major differences between the climate in the present day and pre-agricultural times. When the surface albedo value for cropland is increased in our simulations, the climate response through surface temperature in all three regions becomes significant at the 95% level.

All changes in precipitation, clouds and water vapour from land use change in this study are minor and not significant at any level, except an increasing cloud cover over Europe in CASE 1. We find a total reduction in global surface water flow of −0.6% when considering both vegetation changes and surface albedo changes. This small decrease is a combination of reduced evapotranspiration from the modified canopy (−2.3%) and an increase of evaporation from the surface (+1.8%).

We have shown that the surface albedo value for cropland is of major importance in climate simulations of land cover change. The surface albedo effect is the main driving mechanism when the change in surface albedo between agricultural and natural vegetated land is substantial. Previous estimates of surface albedo of cropland have been less realistic compared to MODIS satellite observations. In our simulations, by increasing the annual global surface albedo by 8% compared to satellite-retrieved values, the surface temperature change between current and pre-agricultural land is closer to previous estimates (Betts, 2001; Hansen et al., 2005; Betts et al., 2007). Using satellite-retrieved surface albedo for cropland, the surface albedo effect becomes smaller and the climate response due to land cover change is weaker. Thus, we explain the disparity in the previously published results on surface temperature change of land cover change. However, we note that differences due to snow cover could also influence this disparity to some extent.

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References

Figure 10. As Figure 4 but for vertical integrated water vapour column (kg m⁻²).


