Contrasting Local versus Regional Effects of Land-Use-Change-Induced Heterogeneity on Historical Climate: Analysis with the GFDL Earth System Model

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Abstract

The effects of land-use and land-cover change (LULCC) on surface climate using two ensembles of numerical experiments with the Geophysical Fluid Dynamics Laboratory (GFDL) comprehensive Earth System Model ESM2Mb are investigated in this study. The experiments simulate historical climate with two different assumptions about LULCC: 1) no land-use change with potential vegetation (PV) and 2) with the CMIP5 historical reconstruction of LULCC (LU). Two different approaches were used in the analysis: 1) the authors compare differences in LU and PV climates to evaluate the regional and global effects of LULCC and 2) the authors characterize subgrid climate differences among different land-use tiles within each grid cell in the LU experiment. Using the first method, the authors estimate the magnitude of LULCC effect to be similar to some previous studies. Using the second method, the authors found a pronounced subgrid signal of LULCC in near-surface temperature over majority of areas affected by LULCC. The signal is strongest on croplands, where it is detectable with 95% confidence over 68.5% of all nonglaciated land grid cells in June–July–August, compared to 8.3% in the first method. In agricultural areas, the subgrid signal tends to be stronger than LU–PV signal by a factor of 1.3 in tropics in both summer and winter and by 1.5 in extratropics in winter. This analysis for the first time demonstrates and quantifies the local, subgrid-scale LULCC effects with a comprehensive ESM and compares it to previous global and regional approaches.

1. Introduction

Land-use and land-cover change (LULCC) has been long recognized as one of the factors affecting near-surface climate (e.g., Bonan 1997; Brovkin et al. 2004; Brovkin et al. 2006; Findell et al. 2007; Pongratz et al. 2010; de Noblet-Ducoudré et al. 2012; Brovkin et al. 2013; Kumar et al. 2013; Mahmood et al. 2013; Christidis et al. 2013). LULCC modifies surface properties, thus affecting all components of the energy and moisture budgets and contributing to the changes in near-surface climate (i.e., biophysical effect). While globally these biophysical effects of LULCC are thought to be small (Findell et al. 2007), regionally they play an important role (Pitman et al. 2009; Findell et al. 2009; Lawrence and Chase 2010; de Noblet-Ducoudré et al. 2012). Additionally, land-use activities alter the amount of carbon stored in the terrestrial ecosystem (Ciais et al. 2013) and therefore contribute to the change of atmospheric CO2 (i.e., biogeochemical effect) and to the anthropogenic warming of climate (Houghton 1999; Arora and Boer 2010; Shevliakova et al. 2009; Shevliakova et al. 2013). The biogeochemical effects of LULCC were recently explored in CO2 emission driven comprehensive ESM models (Shevliakova et al. 2013; Pongratz and Caldeira 2012; Pongratz et al. 2010). There are indications that the effects of global biogeochemical and regional biophysical LULCC-induced climate change cannot be
linearly combined and need to be assessed jointly in order to interpret observed regional climate trends (Jones et al. 2013a,b).

Numerous studies demonstrated that the LULCC has been extensive over the last millennia and the historical period (Ramankutty and Foley 1999; Goldewijk 2001; Hurtt et al. 2011; Pongratz and Caldeira 2012). Deforestation for croplands and pastures generally increases the albedo of the snow-free land surface, leading to a decrease in the surface net radiation (Pielke et al. 2011). In the wintertime in mid- and high latitudes the albedo of deforested lands also increases because snow covers and masks bare ground and shorter vegetation on croplands and grassy pastures more effectively than tree-covered areas. On the other hand, changes in roughness length and associated changes in the turbulent exchanges between land and the atmosphere modify surface energy balance and could counteract the radiative effect. For example, changes in albedo tend to cool the surface of the cropland relative to the neighboring natural vegetation, while reduction of the cropland roughness length tends to warm it in summer season, by reducing the upward heat fluxes leaving the surface. By modifying vegetation properties, such as vertical root distribution and leaf area index (LAI), LULCC also affects the hydrological regime of the plant–soil system, which can in turn create positive or negative feedbacks on the land–atmosphere fluxes (Findell et al. 2007).

Understanding and evaluation of the LULCC biophysical effect has a number of challenges, such as availability of realistic long-term LULCC scenarios and their implementation in land models (Pielke et al. 2011; Hurtt et al. 2011), separation of the LULCC climate signal from the unforced variability in the climate models using simulations with multiple ensemble members (Pielke et al. 2011), and proper accounting for large-scale nonlocal effects and teleconnections that may result from changes in large-scale atmospheric and ocean circulations caused by LULCC (Pitman et al. 2009). Results of recent studies with atmospheric general circulation models (AGCMs; Pitman et al. 2009, 2011; de Noblet-Ducoudré et al. 2012) show that the AGCMs disagree on the direction and magnitude of the local biophysical LULCC signal in the summertime while generally agreeing on the sign of the changes of the wintertime effect.

To assess the biophysical effect of LULCC, previous studies typically evaluated the difference between two sets of experiments: one with present-day or historical LULCC and another with either potential (undisturbed) vegetation (e.g., Findell et al. 2007) or with preindustrial land-use maps (e.g., de Noblet-Ducoudré et al. 2012). To isolate biophysical effect of LULCC from the biogeochemical effect (i.e., changes in atmospheric composition and their effect on climate), most studies prescribed atmospheric concentrations of greenhouse gases (GHGs), including the atmospheric concentration of CO₂ (e.g., Lawrence and Chase 2010; Davin and de Noblet-Ducoudré 2010; Jones et al. 2013b). Previous analyses typically have focused on differences between experiments (e.g., one with LULCC and one without), relying on few realizations of each experiment, and applied a statistical significance tests to identify regions with the biophysical LULCC signals from the unforced variability “noise” in the climate system (e.g., Chase et al. 2000; Findell et al. 2007; Davin and de Noblet-Ducoudré 2010; Jones et al. 2013a,b). One exception is the study of Kumar et al. (2013); their method aims to reduce weather-related noise by comparing climate change impacts between two neighboring regions with and without land use. The majority of the previous studies focused on the net effect of land-use dynamics (e.g., changes in fractions of natural vegetation, pastures, and croplands) and ignored complex subgrid land dynamics such as shifting cultivation in tropical regions and vegetation wood harvesting and regrowth worldwide (e.g., Lawrence and Chase 2010; Jones et al. 2013b). Furthermore, in many studies that have captured subgrid nature of LULCC, analysis focused on the near-surface atmospheric variables that are averaged over the entire grid cell (e.g., atmospheric 2-m temperature), even if the LULCC occurred only in a fraction of grid cells (e.g., Pitman et al. 2009; Lawrence and Chase 2010). At the same time, numerous studies have demonstrated that changes in the local surface characteristics strongly affect local climate—the best-known example of such local LULCC-induced climate effect is an urban heat island phenomena (Mahmood et al. 2013).

In this study we examine effects of LULCC on a multitude of spatial scales from local to regional to global, using the comprehensive Geophysical Fluid Dynamics Laboratory (GFDL) Earth System Model, ESM2Mb (Dunne et al. 2012, 2013). ESM2Mb uses a historical LULCC reconstruction from phase 5 of the Coupled Model Intercomparison Project (CMIP5). Unlike many CMIP5 models that use fractions of LULCC as an input, ESM2Mb uses transition rates among four different land-use categories provided by Hurtt et al. (2011). This analysis enables to capture the subgrid dynamics among different land-use categories (Shevliaкова et al. 2009). In ESM2Mb physical components (i.e., ocean, land, atmosphere, and sea ice) are fully interactive, thus enabling a characterization of the entire climate system response to LULCC. The ESM2Mb represents all subgrid LULCC processes specified by the Hurtt et al. (2011) historical reconstructions, including deforestation of primary and secondary lands for cropland and pasture, shifting
cultivation in tropics, and secondary and primary wood harvesting and agricultural land abandonment.

The land component of ESM2Mb (Dunne et al. 2012, 2013), LM3.0, has a unique treatment of subgrid heterogeneity (Shevliakova et al. 2009; Milly et al. 2014). Like many other terrestrial models, it represents the land in every grid cell as a mosaic of subgrid-scale tiles with distinct physical and ecological properties. Unlike most other CMIP5 models, land tiles in GFDL models have distinct soil column properties. Each tile has distinct energy and moisture balances for a vegetation–snow–soil column, biophysical properties, and exchanges of radiant and turbulent fluxes with the overlying atmosphere. LM3.0 predicts physical, biogeochemical, and ecological characteristics for each subgrid land surface tile from the top of the vegetation canopy to the bottom of the soil column including leaves and canopy air temperature, canopy-air-specific humidity, stomatal conductance, snow cover and depth, runoff, vertical distribution of soil moisture, ice, and temperature. To our knowledge, none of the previous fully coupled climate models and ESM studies have captured the implications of LULCC-induced heterogeneity in the land state below ground. The separation of soils under different land-use tiles in GFDL ESMs allows the investigation of the LULCC effects not only on vegetation, but also on the state of the soil and their combined feedbacks on climate.

2. Methods and models

a. Earth system model

In this study we use the GFDL ESM2Mb model, which is very similar to the GFDL ESM2M model described in Dunne et al. (2012, 2013), except few land parameters (i.e., mortality rates for evergreen coniferous trees and their branch-wood turnover rates) were set to values from the GFDL ESM2G, which reduces the global biomass biases in the model (Dunne et al. 2013). The atmospheric and land components have a 2° latitude by 2.5° longitude horizontal resolution with 24 vertical levels in the atmosphere. Ocean component has a 1° horizontal grid up to 1½° meridionally at the equator and tripolar above 65°N, with 50 vertical levels. Ocean biogeochemistry component is Tracers for Ocean Phytoplankton with Allometric Zooplankton version 2.0 (TOPAZ 2.0). The sea ice component represents full ice dynamics, three-layer thermodynamics, and five different ice thickness categories plus open water on the same grid as the ocean. The coupling between components enforces energy, mass, and tracer conservation.

b. Land model

Similarly to other GFDL ESMs, ESM2Mb includes land component LM3.0, described in detail in Milly et al. (2014). Here we describe LM3.0 features relevant for the subject of this study.

Evapotranspiration in the model includes water vapor flux from the soil and/or snow cover, from liquid and solid canopy interception, and plant transpiration. The transpiration is a function of plant stomatal conductance, which is prognostically computed as part of photosynthesis parameterization (Farquhar et al. 1980; Collatz et al. 1991, 1992; Leuning 1995). Soil water availability for transpiration is a function of vertically resolved distributions of plant roots and soil moisture in each land surface tile. In each layer, the model solves Richards’s equations (Richards 1931) in the vicinity of fine roots, given their biomass and properties (e.g., fine root radius and resistance of the root skin to water flow; Milly et al. 2014) and soil moisture in a layer. As a result, the water availability and transpiration equations take into account the amount of roots per layer, root and soil properties, and the soil moisture, which all can be affected by the LULCC. Every natural and LULCC subgrid land tile interacts with its own soil water.

For radiative transport, the vegetation canopy is treated as a dispersed medium where canopy reflectance is dependent on leaf properties and amount of intercepted snow. The canopy is underlain by a reflective, opaque surface of soil and/or snow, with extent of snow as a function of snow depth. Additionally, sufficiently deep snow can mask a fraction of the canopy itself. Bare soil radiation parameters were specified from the Moderate Resolution Imaging Spectroradiometer (MODIS) bidirectional reflectance distribution function (BRDF) parameters (Milly et al. 2014). Snow BRDF parameters were also assigned on the basis of MODIS observations from regions with little or no vegetation, such as large frozen lakes (Milly et al. 2014).

The terrestrial component of ESM2Mb LM3.0 simulates vegetation dynamics as described by Shevliakova et al. (2009). It simulates changes in vegetation and soil carbon pools, anthropogenic carbon storages, as well as the carbon exchange among these pools and the atmosphere. Vegetation carbon is partitioned into five pools: leaves, fine roots, sapwood, heartwood, and labile storage. The sizes of the pools are modified daily depending on the carbon uptake and according to a set of allocation rules. Additionally, the model simulates changes in the vegetation carbon pools due to phenological processes and natural mortality and fire. LM3.0 represents vegetation as five dynamically competing vegetation types: deciduous, coniferous, and tropical trees, as well as...
warm and cold grasses. Since the height of the plants, their LAI, and seasonality of leaf cover are determined prognostically in each vegetation tile, the five types can capture a variety of global biome characteristics.

The land-use history is prescribed from the Hurtt et al. (2011) reconstruction for each grid cell in terms of transition rates among four distinct land-use types: undisturbed (natural), crops, pastures, and secondary vegetation.

The transition-based approach employed in LM3.0 creates more land-cover disturbance than the fraction-based approach used by many other models (Shevliakova et al. 2013) because the transitions capture not just net but gross subgrid changes among different land-use types, including shifting cultivation and secondary vegetation harvesting (secondary-to-secondary transition). For example, the sum of all transitions among four land-use types (natural, cropland, pasture, and secondary) in Hurtt et al. (2011) reconstruction over the period 1861–2005 was $195.3 \times 10^6$ km$^2$, while the net increase of area disturbed by LULCC over the same time was $48 \times 10^6$ km$^2$. The transition-based approach eliminates one of the uncertainties associated with the LULCC implementation protocol (Pielke et al. 2011): the transition rates among all land-use type reflect paths of changes not just net effect. To illustrate the state of the land use in the period discussed in this study, Fig. 1 shows fractions of each land-use type averaged over 1986–2005.

In LM3.0, land-use transitions are applied annually at the end of the calendar year by splitting the parts of the tiles that undergo transitions in each grid cell and forming new (i.e., secondary) tiles after agricultural abandonment and forest logging (Shevliakova et al. 2009). In addition, secondary tiles in a grid cell with similar biological and physical characteristics are merged. Croplands, pastures, and natural vegetation each assigned one tile per grid cell, but several tiles can be assigned to secondary vegetation to keep track of the age distribution of secondary lands.

In ESM2b croplands and pastures are harvested annually but with different intensity. On croplands, harvesting removes a significant fraction of total biomass, leaving only 0.1 kg C m$^{-2}$ for the next year’s growth; on pastures, only 25% of leaf biomass is removed every year. Harvesting is applied at the end of calendar year (31 December; Shevliakova et al. 2009). Secondary vegetation is defined in this model as the vegetation regrowing in areas previously disturbed by LULCC and not currently managed. This includes all abandoned agricultural land as well as the land where wood was harvested at least once in prior years. As in Hurtt et al. (2011) reconstruction, secondary lands never return to undisturbed (natural) category—the secondary vegetation and underlying soils are in a state of recovery from disturbance. The stage of this recovery depends on the
nature of disturbance (abandonment or wood harvesting), time since last disturbance, and environmental conditions. The model keeps track of different recovery stages by creating a secondary vegetation tile every time a disturbance occurs and simulating the vegetation regrowth in the tile. Consequently, in the naturally forested areas secondary tiles created by recent disturbance have biomass significantly lower than the neighboring undisturbed vegetation. The properties of old secondary vegetation tiles are much closer to the undisturbed forests. To avoid unrestricted growth of the number of tiles (and, hence, the computational burden) the secondary vegetation tiles are merged if their properties are sufficiently similar (Shevliakova et al. 2009), while preserving water, energy, and carbon balances.

In the simulations discussed in this manuscript, we limit the maximum number of secondary vegetation tiles to 10. In LM3.0, the influence of fires is taken into account as reduction of vegetation biomass, changes in carbon emissions, and inputs of carbon to soils.

By construction, there is no irrigation in LM3.0. The type of vegetation in the disturbed tiles is predicted by vegetation dynamics module and is based on the running averages of simulated climatology and biomasses (Shevliakova et al. 2009). Depending on environmental conditions ESM2Mb cropland tiles are C3 or C4 grasses because high intensity of harvesting prevents establishment of the forests. However, in the model, pastures can overgrow with trees because grazing is assumed to only remove 25% of the leaf biomass annually.

c. Experiment design

To examine the influence of LULCC on the land surface climate we conducted two sets of ESM2Mb numerical simulations with five ensemble members each: a historical land-use experiment (LU) and a potential vegetation (PV) experiment. Both sets of experiments used full set of CMIP5 historical atmospheric forcings (Taylor et al. 2012), which included greenhouse gas concentrations (Meinshausen et al. 2011), tropospheric and stratospheric ozone concentrations (Cionni et al. 2011), solar forcing (Lean 2009), volcanic aerosols (Stenchikov et al. 1998), and tropospheric aerosols (Lamarque et al. 2010). The LU experiment used the historical land-use scenario (Hurtt et al. 2011), while the PV experiment did not apply any land-use transitions and had undisturbed natural (i.e., potential) vegetation everywhere.

We initialized the ESM2Mb control simulation after 2100 years of the ESM2M spinup with preindustrial forcing (Dunne et al. 2012, 2013). At this time, we changed vegetation parameters to those of ESM2Mb and ran 2000 years of a preindustrial (PI) control simulation. Starting from year 800 of the PI ESM2Mb control run, we branched off the LU historical simulation ensemble members every 100 years until we reached five members. Each LU ensemble member ran for 306 years (1700–2005), with first 161 years (1700–1860) of simulations affected only by the land-use changes in order to capture effect of transient LULCC on the 1860 land conditions (Sentman et al. 2011). The first PV ensemble member was branched off year 962 of the PI control, with following ensemble members branched off every 100 years. The branching dates of the PV experiments were chosen to avoid possible influence of the very long-term ocean variability on the results, so that the time from the beginning of PI control to the start of the 1861–2005 period was the same as for respective member of the LU ensemble.

3. Local LULCC climate contrast

In this section, we analyze the results of the historical (LU) experiment only. Since the model keeps track of climate in each of the four land-use types, it allows us to examine the local climate contrast defined as a difference in climate states among different land-use types within each grid cell (see Fig. 2a). All land-use tiles within the grid cell receive the same input from the atmosphere (downward shortwave and longwave radiation, precipitation as well as temperature, specific humidity, wind speed, and surface pressure). The physical and ecological states and properties of the land surface tiles are different, and the fluxes between land and the atmosphere are calculated separately for every tile.

a. Choice of near-surface temperature

The weather/climate is inherently chaotic, and many modes of such unforced variability on a wide range of time scales are captured by the comprehensive ESMs (Flato et al. 2013). In two different numerical experiments (e.g., LU and PV ensembles described above), internal climate variability will unfold differently (e.g., weather systems will come and go at different times, El Niño will happen in different years) and thus it will obfuscate the signal because of the difference in forcing (i.e., LULCC). However, when we contrast values of ESM2Mb land variables or land–atmosphere fluxes among tiles in the same grid cell in the same LU experiment, we are not introducing a different realization of climate variability from another experiment and are observing the signal from the LULCC only. Each of the tiles experiences the same climate variability of the atmospheric input forcing on all time scales. For example, the variations of canopy air temperatures of natural vegetation $T_{can}$ and cropland $T_{can}$ are going to be of the same order as the variations of atmospheric temperature.
However, since both tiles are in the same grid cell, their temperatures are synchronously driven by the same atmospheric conditions, so the variations of $T_{caN}$ and $T_{caC}$ are not independent. Therefore, the difference $T_{caC} - T_{caN}$ reflects more effects of LULCC forcing and not as much atmospheric climate variability between different experiments, thus amplifying the signal-to-noise ratio. For example, using paired-difference Student’s $t$ test, $T_{ca}$ difference between croplands and natural vegetation in June–August (JJA) is statistically significant with 95% confidence for 90.9% of points where croplands exist, or 68.5% of all nonglaciated land grid cells. Calculations of temperature contrast between other land-use types and in other seasons give similar numbers.

Most previous studies (Bonan 1997; Findell et al. 2007, 2009; de Noblet-Ducoudré et al. 2012) used temperature at 2 m above displacement height to detect the influence of the LULCC on surface climate. In this study, we are analyzing canopy air temperatures ($T_{ca}$) to capture land surface climate effects. LM3.0, like many other land surface schemes (e.g., Deardorff 1978; Sellers et al. 1996; Dai et al. 2003), considers the temperature of the air space within the vegetation canopy $T_{ca}$ to be an independent prognostic variable. The model neglects thermal inertia of the canopy air and radiative effects in the canopy air, so the evolution of $T_{ca}$ is driven by the sensible heat fluxes that canopy air exchanges with atmosphere, vegetation canopy, and ground surface.
calculated separately for each subgrid tile. The turbulent flux exchange between canopy air and atmosphere is calculated using Monin–Obukhov similarity theory (Anderson et al. 2004). The fluxes between canopy air and vegetation canopies, and between canopy air and the ground surface, are calculated using approach of Bonan (1996).

The 2-m air temperature $T_{\text{ref}}$, being an interpolation between $T_{\text{atm}}$ and $T_{\text{ca}}$, is closer tied to the state of the atmosphere than the state of the land (e.g., canopy air, leaves, ground, soil), and therefore is more likely to attenuate implications of LULCC for land surface climate. Besides, in the models the 2-m elevation for the temperature reporting is typically measured from the displacement height ($z_{0h}$; 20–30 m). To calculate 2-m temperature, the model uses the following expression in each tile:

$$T_{\text{ref}} = T_{\text{atm}} \frac{F(z_{\text{ref}})}{F(z_{\text{atm}})} + T_{\text{ca}} \left[1 - \frac{F(z_{\text{ref}})}{F(z_{\text{atm}})}\right],$$

where

$$F(z) = \ln \left(\frac{z}{z_{0h}}\right) - \Psi_{H}(z).$$

Here, $\Psi_{H}$ is integral similarity function for moisture and tracers (Anderson et al. 2004), $z_{0h}$ is roughness length for heat, $z_{\text{ref}} = 2$ m, and $z_{\text{atm}}$ is the height of the lowest atmospheric layer above zero-plane displacement plane ($z_{\text{atm}}$ depends on the surface elevation and atmospheric parameters; typically it is about 35 m at the sea level in the model configuration described here); $T_{\text{ref}}$ gridcell value is then just the area weighted average of the tile values in the grid cell.

Consequently, $T_{\text{ca}}$ could be considered a more suitable measure of near-surface land climate relevant to understanding of LULCC impacts on environment surrounding plants, crops, animals, and humans than 2-m reference temperature.

b. Near-surface temperature contrasts among land-use types

Figure 3a shows the annual-mean canopy air temperatures of undisturbed (natural) tiles averaged over the last 20 years of the historical simulations (1986–2005). Figures 3b–d show differences between canopy
The annual-mean response to anthropogenic land-cover change tends to be a cooling in the high latitudes and a warming in the low latitudes, with values for croplands (the most perturbed part of land) between \(-2.5\) and \(3.3\)°C. The annual pattern arises from a differential response across seasons, particularly summer and winter, as discussed below, and in section 4c.

Figure 4a illustrates the summertime canopy air temperature averaged over the last 20 years of the historical simulation (1986–2005). For the Northern Hemisphere the figure shows boreal summer (JJA) average, for Southern Hemisphere DJF average. (b),(c),(d) The canopy air temperature differences between different types of land disturbed by LULCC (crops, pastures, and secondary vegetation, respectively) and natural vegetation within grid cells within the same integration.

In the winter season (Fig. 5), the disturbed vegetation tiles are generally cooler than the undisturbed tiles except some tropical areas and Tibet. Similarly to the regions (grasses) have similar properties. The warmer summer on croplands is consistent with the lower biomass of croplands, which leads to the largest differences in vegetation and surface properties. The lower biomass of crops, compared to pastures, is the result of the more intense harvesting. As noted above, secondary vegetation is recovering from LULCC disturbances, so over time (e.g., multiple decades for forests) its vegetation state becomes similar to natural (undisturbed) vegetation and, as a result, the surface climate differences between recovering secondary and the undisturbed vegetation tiles are expected to decrease over time (although biogeochemical differences, i.e., soil carbon, could persist for centuries). However, Fig. 4d still shows noticeable temperature differences between secondary and undisturbed vegetation. Within each grid cell, there are recently disturbed secondary tiles with properties not yet close to undisturbed vegetation. Therefore, they show the effects similar to croplands and pastures, diluted by the averaging with older secondary tiles.
summer season, the largest surface air temperature difference is between croplands and natural vegetation (larger than 1°C in most extratropical regions, with the minimum of −4°C), because of the large difference in the vegetation properties (albedo, etc.), particularly in the snow-covered regions.

c. Physical mechanisms of temperature response

This section focuses on analysis of the land surface energy balance (i.e., the net short- and longwave radiation, latent and sensible turbulent heat fluxes) associated with the near-surface temperature difference between cropland and undisturbed (natural) vegetation tiles. The cropland–natural pair is selected because the contrast in land surface proprieties and temperature is the largest among all land-use tiles (see Figs. 4 and 5) and provides the clearest case for the analysis.

Figure 6 shows the differences in the components of the surface energy balance between croplands and natural (undisturbed) vegetation: the net short- and longwave radiation and latent and sensible turbulent heat fluxes. The net shortwave flux (Fig. 6a) of croplands is lower than that for natural vegetation by 2–5 W m⁻² almost everywhere, indicating that the albedo of croplands in summer is generally higher than that of vegetation undisturbed by LULCC. The net longwave radiation of croplands (Fig. 6b) is also lower, on the order of 2 to 10 W m⁻². This is a consequence of the higher vegetation temperatures in cropland areas, which leads to increase of the upward longwave flux, while the downward longwave radiation is the same for all tiles within a grid cell, by construction. The dependence of the longwave radiation absorptivity on the type of vegetation in the absence of snow is small in this model.

The summertime pattern of the sensible heat flux difference between cropland and natural tiles (Fig. 6c) in extratropics emerges as a result of regional differences in vegetation species dominant on cropland and natural tiles and associated differences in seasonality of their properties. For example, in the eastern United States and Europe, temperate deciduous trees are dominant in the natural vegetation. Their LAI grows sharply from May to June, which increases transpiration, as the area of the transpiring leafs increases. This shifts the balance toward latent heat flux, resulting in positive difference in cropland–natural sensible heat flux, as croplands do not experience the same sharp increase in LAI at that time of year. In coniferous-dominated areas, such as northwest of the United States and Siberia, no such shift in regime occurs, so the sensible heat flux from the croplands remains lower in JJA that from the natural vegetation owing to the difference in properties. In coastal
area of Texas, the combination of the dominant species in croplands (C4 grass, in contrast to C3 grass dominant in on the croplands in the rest of the extratropics) and on natural tiles (tropical evergreen trees) creates a different seasonal cycle of latent and sensible heat fluxes than in the rest of the continent.

The largest contribution to the land surface energy balance change on croplands in summer comes from the reduction of the latent heat flux (Fig. 6d) in almost all locations except some relatively small areas. In ESM2Mb, the reduction of latent heat flux over croplands (by \(-20 \text{ W m}^{-2}\) in most of the United States, Europe, and China) does not appear to be caused by relative lack of water in cropland soils. On the contrary, in general the soil water content in the upper 30 cm of the soil is higher by 2% to 20% of saturated values (2 to 15 kg m\(^{-2}\)) on croplands, as shown in Fig. 7a. Rather, the reduction of water vapor flux to the atmosphere is caused by changes in the vegetation properties. The cropland LAI and root biomass values are smaller than those of the undisturbed vegetation; therefore, the ability of vegetation to transpire and evaporate intercepted water is also smaller. Since the rainfall rate is exactly the same in all tiles in each grid cell, the reduction in evapotranspiration leads to an increase of soil water in the cropland tiles. The changes in runoff do not play critical role in this process in this model since there is no horizontal water transport in the soil among tiles or grid cells. It is not possible to simulate soil water redistribution effect described above in most other CMIP5 climate models and ESMs because they do not separate soil water columns under different land-use tiles.

The LM3.0 model used in this study did not include representation of the lateral groundwater transport between the tiles, under implicit assumption that the tiles are large enough for such transport to be negligible in the overall water balance. This is not necessarily the case in the real world, where lateral groundwater flow due to differences in elevation may be important for the soil moisture and, therefore, for the state of the vegetation. While recently significant progress has been made in this direction (Li et al. 2013; Kleinen et al. 2012; Hilberts et al. 2007), the issues of the interaction between topographically induced soil moisture and vegetation heterogeneity and land-use practices remains open and important topic of future research.

In the tropical areas, the seasonality of cropland–natural temperature contrast is dominated by the seasonality of the harvesting in the model, in combination
with the seasonality of the precipitation. Harvesting, applied in the model annually at the end of calendar year, significantly reduces LAI of the croplands (from 3.7 m$^2$ m$^{-2}$ in December—the month before harvesting—to 0.7 m$^2$ m$^{-2}$ in January in the 10$^\circ$S–10$^\circ$N region) and their root biomass, leading to significant reduction in latent heat flux (by 17.3 W m$^{-2}$ compared to the natural vegetation in January after harvesting) and corresponding increase of the temperature of the croplands compared to that of neighboring natural vegetation. After the harvesting, the cropland vegetation regrows, and therefore its properties (e.g., LAI, roughness, and reflectance) become closer to the values found in the natural vegetation tiles. Because the contrast of the physical properties decreases, cropland temperature is generally closer to the temperature of undisturbed vegetation later in the year than right after harvesting. Figure 8 shows the difference of canopy air temperature between croplands and natural vegetation for three consecutive months straddling the model harvesting date (31 December). While the temperature difference in high- and midlatitudes of the Northern Hemisphere does not show abrupt changes, there is clear contrast between December and January in the tropics and in southern subtropics, associated with sharp change in vegetation properties after the harvesting date. The December–February (DJF) seasonal pattern is dominated by the January–February pattern.

Strong regional reaction of temperature to the harvesting on monthly time scale emphasizes importance of the accurate representation of agriculture seasonality for modeling of physical effects of LULCC. While in real world we can also expect abrupt changes of land surface properties at the moment of harvesting, those changes occur at different times in different regions, depending on climate, crop type, and cultural differences in agricultural practices (Sacks et al. 2010). Improving model representation of agriculture, including representation of different harvesting schedules and properties of different crops, is an important topic of our future research.

Figure 9 shows the difference in surface fluxes between crops and undisturbed vegetation for the winter season. The net shortwave radiation is reduced over croplands in high and midlatitudes in winter by up to 15–20 W m$^{-2}$ because snow covers shorter vegetation and bare ground more effectively. The geographical pattern of the cropland–natural net shortwave radiation difference (Fig. 9a) in the snow-covered regions reflects the pattern of the dominant vegetation: the magnitude of difference is larger in the regions where the contrast between the wintertime optical properties of natural cover and croplands is the highest (e.g., in the regions naturally covered by the evergreen forests). The relatively minor increase in the net longwave radiation is simply a reflection of the lower outgoing longwave radiation from croplands because of their lower temperature in the winter, compared to forested undisturbed tiles.

In the wintertime, one unexpected feature of the pattern of turbulent flux changes (Fig. 9) is the opposite sign of the latent and sensible heat flux changes over croplands in midlatitudes of the Northern Hemisphere. Sensible heat fluxes in the cold seasons in high and midlatitudes are well known to be negative on monthly time scales (e.g., Harding et al. 2001; Falge et al. 2005), while latent heat flux is directed upward even in winter. The changes in these two turbulent fluxes largely compensate each other, with magnitude around 5 W m$^{-2}$. As a result, the net shortwave radiation reduction dominates and leads to a cooling of the near-surface temperature in cropland tiles. Since in the model both sensible and latent heat fluxes between canopy air and the atmosphere are
determined by the same turbulent exchange processes, and the near-surface turbulent exchange coefficients for heat and water vapor are the same, the sign difference in the fluxes looks counterintuitive. The explanation is that in the winter season the sensible and latent heat fluxes transfer heat in different directions: sensible heat flux tends to warm the surface, and the latent heat flux carries energy from the surface to the atmosphere. Reduction in

![Canopy air temperature difference between cropland and natural tiles for three consecutive months: (a) December, (b) January, and (c) February. Data are averaged over ensemble and over 20 years of simulation (1986–2005).](image-url)
surface roughness of the croplands and associated re-
duction of the turbulent exchange coefficient results in
reduction of the magnitude of the fluxes. This decrease in
magnitude produces the pattern seen in Figs. 9c,d. This
also explains why this effect occurs only in mid- and high
latitudes, where the seasonally averaged latent and sen-
sible fluxes have different signs.

The physical mechanisms discussed above also work
for pastures and recently disturbed secondary vegeta-
tion tiles, albeit with different magnitudes. Pastures
have higher biomasses than crops as a result of less in-
tense harvesting, so the differences in surface energy
perturbations relative to undisturbed (natural) will be
smaller. As a result, differences in near-surface tem-
perature with the natural vegetation will also be smaller,
as can be seen in Figs. 4b and 5b. The same is true for the
secondary–natural energy balance and temperature
difference, except that the secondary vegetation in the
model is not single tile, but a number of the tiles in
different stages of recovery. While recently disturbed
secondary tiles have relatively low biomass compared to
the undisturbed vegetation, the older secondary tiles
will be closer to the properties of the undisturbed veg-
etation, diluting the effects discussed in this section. The
net effect, therefore, will depend on the proportion of
recently disturbed versus older tiles (i.e., on the history
of disturbances).

4. Regional and global climate effects of LULCC

In this section, we examine biophysical effects of land
use on the global and regional scales. On larger scales,
the local subgrid effects discussed in section 3 are di-
minished by the averaging with undisturbed portions of
the grid cells. Furthermore, interaction with the atmo-
sphere and the rest of the climate system may lead to the
teleconnections, as has been hypothesized by Pitman
et al. (2009). Similarly to previous studies, we analyze
the difference between the ensembles of PV and LU
experiments. Figure 2 illustrates the differences be-
tween the two kinds of experiments. The results de-
scribed in this section contrast the near-surface climate
differences of gridcell averages between cases illustrated
by Figs. 2a and 2b. The near-surface temperature ana-
yzed in this section is a combination of canopy air
temperature above the land and sea surface temperature
over the ocean, unless explicitly specified otherwise.

Global-mean near-surface temperatures (Fig. 10a)
increase with time in both PV and LU experiments in
response to historical natural and anthropogenic
The global-mean temperature averaged over years 1861–2005 is warmer in LU experiment by 0.03\degree K, and the temperature averaged over land is warmer by 0.05\degree K. While both these values are small, they are statistically significant with 95% confidence. The globally averaged temperature differences between LU and PV experiments are very similar regardless of which temperature—canopy air ($T_{ca}$) or 2 m ($T_{ref}$)—we use.

To estimate statistical significance, we used paired-difference Student’s $t$ test with the number degrees of freedom adjusted to take into account system memory (von Storch and Zwiers 1999). Most of previous studies report global annual-mean cooling due to LULCC (e.g., Davin and de Noblet-Ducoudré 2010; de Noblet-Ducoudré et al. 2012; Jones et al. 2013b); however, some discovered a weak warming effect (e.g., Findell et al. 2007; Lawrence and Chase 2010).

Global-mean precipitation also increases (Fig. 10b) as the planet warms, consistent with the tendency of the hydrological cycle to intensify with the climate warming (Manabe et al. 1981; Held and Soden 2006). While both global-mean and land-averaged precipitation in LU experiment is slightly lower than that in PV (Figs. 10b,d), the difference is not statistically significant given the background of natural variability, even with five-member ensembles.

Figure 10 shows that over the course of simulation, the global-mean response to the land use does not change dramatically in magnitude. Also, it demonstrates that the period we analyze in detail (1986–2005) is not anomalous in terms of global-mean response.

Figures 11a,b,c,d show the differences of the ensemble-mean seasonal temperature and precipitation between LU and PV experiments averaged over the last 20 years of the simulations (1986–2005). To estimate statistical significance of the differences between 20-yr seasonal averages, we used a modified Student’s $t$ test for small samples (Zwiers and von Storch 1995), applied to the ensemble averages of the variables. This test is more rigorous than original $t$ test because it takes into account the autocorrelation within the time series. Since the memory of the system is much longer over the oceans, the autocorrelation of time series is higher, resulting in very few significant differences over the oceans in all panels of Fig. 11.

Figure 11 reveals a number of regions where LULCC causes a statistically significant response, similar to findings of Pitman et al. (2009) and Lawrence and Chase (2010). The pronounced warming in JJA in North America and Europe is caused by the interaction between LULCC and the atmosphere that was also reported in previous studies (e.g., Findell et al. 2007, 2009; Pitman et al. 2009; Lawrence and Chase 2010). Changes of vegetation properties due to LULCC reduce evapotranspiration, as discussed in section 3c and Fig. 6d.
Fig. 11. Maps of near-surface (a),(b) temperature, (c),(d) precipitation, (e),(f) latent heat flux, and (g),(h) downward shortwave radiation at the surface difference between full historical and potential vegetation experiments (LU–PV) averaged over the last 20 years of the historical integration (1986–2005). Regions that are statistically significant with more than 95% confidence are hatched. Canopy air temperature is used over the land and surface temperature over the ocean.
Consequently, we see the reduction of latent heat flux compared to the PV (Fig. 11e). This change tends to warm the surface as the balance shifts toward the sensible heat flux. Reduction of evapotranspiration in these regions also results in drier atmosphere and, therefore, reduced precipitation (Fig. 11c). This process creates a positive feedback in the coupled system, so that the upper soil is also drier in LU experiments compared to PV in North America and Europe, opposite to the sign of local contrast between croplands and natural vegetation as shown in Fig. 7. Importantly, the cloud fraction is also reduced over the regions of high LU–PV temperature contrast in North America and Europe by 2%–5%, resulting in an increase of downward shortwave radiation flux at the surface (Fig. 11g), which further contributes to the increase of near-surface air temperature in LU experiments.

The geographical pattern of response emerges from the combination of the pattern of intense LULCC (Fig. 1), geographical pattern of natural forests, and interaction with the atmosphere. In the regions of natural grasslands physical properties of disturbed and undisturbed lands are not dramatically different, and therefore near-surface climate is not disturbed to the same degree by LULCC of the same intensity as in the forested regions. Other naturally forested regions of intense land use (India and China) show a similar pattern of temperature and downward radiation response, albeit smaller in amplitude than Europe and North America. The difference is perhaps due to regional differences in atmospheric transport of heat and water vapor, which do not create positive feedback noted above.

To quantify climate changes due to LULCC, and to compare our results with the results obtained by Land-Use and Climate, Identification of Robust Impacts (LUCID) studies with other models, we follow the approach of (Pitman et al. 2009) and define the regions of intense land use as the land area where LAI differences between PV and LU experiments (averaged over all land-use types) are larger than 0.5 m$^2$ m$^{-2}$. By this definition, 25.9% of land points are classified as the region of intense land use in JJA and 16.1% in DJF. For JJA, 32.7% of the points within the regions of intense land-use change exhibit statistically significant changes in temperature and 3.2% in precipitation (Table 1, Figs. 11a and 11c). Outside of the regions of intense land use, only 0.8% of points are statistically significant different in temperature and 0.3% in precipitation. This is consistent with the results of Pitman et al. (2009) reported for other models.

If we apply similar statistical analysis to the 2-m air temperature (instead of combination of canopy air and sea surface temperature), only 17.6% of the points within the regions of intense LULCC show significant differences in temperature in JJA, compared to 32.7% if we use canopy air/sea surface temperature. Thus, a choice of climate variable itself has significant implication for measuring the strength if LULCC effect. Both values are within the range of LUCID study (Pitman et al. 2009), albeit the value for 2-m air temperature is close to the lower end of spread of participant models (approximately 17%).

The total percentage of grid cells where LU–PV temperature difference is statistically significant changes in roughly the same proportion depending of what temperature we analyze: globally, 5.8% of all grid cells are significant if we use combined canopy air/sea surface temperature and 3.7% for 2-m air temperature. For nonglaciated land these numbers are 8.3% and 4.4%, respectively. Since for 95% confidence interval the statistical significance test can randomly reject 5% of the points (von Storch and Zwiers 1999), the difference in temperature is only formally detectable over nonglaciated land if we use canopy air temperature, even though over region of intense land use both canopy air and 2-m temperature show noticeable responses.

The DJF response is weaker than the JJA, with only 16.8% of the points within the regions of intense land use showing significant temperature effect and 1.7% points detectable precipitation change (Figs. 11b and 11d, respectively). The responses of annual-mean temperature and precipitation (not shown) are also weak relative to JJA, with 17% and 4.4% of the points within intense LULCC regions experiencing detectable changes in temperature and precipitation, respectively.

5. Relationship between local climate contrast and regional LULCC

In this section, we investigate how subgrid climate contrast caused by LULCC relates to the larger-scale climate effects, described here as differences between the LU and PV climates. Our simulations allow us to look both at the contrast between the near-surface

| Table 1. Percentage of the points within and outside the regions of intense land use that show statistically difference between full historical and potential vegetation experiments (LU – PV) over the last 20 years of the historical integration (1986–2005). The regions of intense land use are defined as in LUCID studies (Pitman et al. 2009). |
|---|---|---|---|---|
| Significance within | T, JJA | T, DJF | P, JJA | P, DJF |
| Significance within | 32.7 | 16.8 | 3.2 | 1.7 |
| Significance outside | 0.8 | 0.6 | 0.3 | 0.2 |
temperature of specific land-use types in LU experiment and the near-surface temperature in the PV simulations.

Figures 12a and 13a show scatterplot diagrams of JJA and DJF temperature differences, respectively, illustrating the relationship between subgrid and regional LULCC effects. Each point in the cloud represents a single grid cell. In all six panels of each figure the vertical axis is the canopy air temperature contrast between the agricultural portion of the grid cell, and natural vegetation in the same grid cell in LU simulation, averaged over all ensemble members and over 1986–2005 period for JJA. Horizontal axis is the difference of the gridcell average canopy air temperatures for the same grid cells between LU and PV simulations. Orthogonal distance regression lines are shown in black. (a) Entire globe, (b) tropical region (equatorward of 23.44°), and (c) extratropical region (poleward of 23.44°). Each point represents a single grid cell. Different colors mark grid cells with different fraction of agricultural land, as indicated in the legend. (d),(e),(f) Averages and standard deviations of points in (a),(b), and (c), respectively.

The cloud of points for DJF season in Fig. 13a has larger spread along the local contrast (vertical) axis than along the LU–PV (horizontal) axis: 0.56°C versus 0.32°C. The spread in two directions is controlled by two different mechanisms: along the vertical axis it is the subgrid contrast between disturbed and undisturbed portions of the grid cells, while on the horizontal axis, the disturbed/undisturbed temperature contrast is diluted by the gridcell averaging and by internal climate variability between the LU and PV experiments. Note that a subset of points is spread along horizontal zero line, with small vertical extent. These are the points that experience little subgrid contrast because of conversion to the agriculture (e.g., because they are located in

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natural grasslands, where vegetation properties of natural and disturbed tiles are similar, but the contrast between LU and PV experiments still exists. In DJF, LU–PV temperature differences averaged over the regions of different LU intensity are small, as shown in Fig. 13d, where the points cluster about zero along the horizontal axis. The spread of the averages of local contrast (along the vertical axis in Fig. 13d) is larger, although the averages are still within one standard deviation from each other.

Figures 12b,c and 13b,c show the same scatterplot diagram, but for tropical (equatorward of 23.44° latitude) and extratropical (poleward of 23.44° latitude) portions of the land surface. In DJF, the local contrast in tropics is largely positive (cf. Figs. 4 and 5), with averages approximately 0.3°C above diagonal line of equal local contrast and LU–PV difference. In extratropics, the local temperature contrast shows cooling of the disturbed parts of the land, and it is still larger in magnitude than the LU–PV contrast.

The slopes of regression lines for global, tropical, and extratropical land are 1.89 ± 0.05, 1.33 ± 0.05, and 1.45 ± 0.05 respectively, indicating that the subgrid signal is stronger than LU–PV difference everywhere in DJF. Here and below, the numbers following the symbols ± are the uncertainty (1σ) of the regression coefficients and not confidence intervals.

The pattern is somewhat different in JJA (Fig. 12), where the cloud of points is spread more or less around the diagonal line of equal contrasts, with approximately equal standard deviations (0.39°C for local contrast and 0.37°C for LU–PV difference for the entire cloud of points). Tropical local temperature contrast is again higher than the LU–PV difference by about 0.15°C (Fig. 12e). In the extratropics there is no clear signal. The characteristic cloud of points spread around zero local contrast line that is caused by variability in LU–PV difference over the regions of low local temperature contrast is also clearly visible in JJA (Figs. 12a,c). The regression slopes for JJA are 0.95 ± 0.02, 1.36 ± 0.04, and 0.82 ± 0.02 for global, tropical, and extratropical land, indicating that the subgrid response is stronger than LU–PV in tropics this season but not in the extratropics.

The reason for the slope of the regression line being less than 1 in the extratropics in JJA (Fig. 12c) is the amplified response to LULCC in LU experiments. As discussed in section 4, in few extratropical regions...
(Europe and part of North America) positive feedback between LULCC and the atmosphere through reduction of evapotranspiration creates LU–PV temperature differences that can be higher that the local contrast among tiles in the LU experiments, considering also that the climate in LU experiments is drier than in PV owing to aforementioned feedback. Consistently with the discussion in section 4, the slope would have been even lower if we only used regions of intense land use for the regression.

The locations of the cloud averages shown in Figs. 12d,e,f and 13d,e,f appear to follow a pattern as the fraction of agriculture increases. Partly this is due to decrease of the dilution effect with the agricultural fraction: as the fraction of agriculture in a grid cell increases, the average temperature of the grid cell gets closer to the temperature of the agricultural portion. However, another important factor is the location of the grid cells with different agricultural fractions: the regions of land use of different intensity are not spread randomly over the land but tend to be concentrated in regions with favorable to agriculture climates (Figs. 1b,c). Therefore, the regional differences in climate response to land-use change also play role in creating such patterns.

It appears that, in general, the relationship between local temperature contrast between agricultural and undisturbed fractions of the land and the LU–PV difference in temperatures is complex and varies by season, by region, and with fraction of undisturbed vegetation in the grid cell.

While Pitman et al. (2009) and de Noblet-Ducoudré et al. (2012) studies examined atmosphere/land simulations with prescribed SST, in this study we explore responses of the fully interactive climate systems to LULCC. The latter allows the possibility of amplifying remote climate responses to local LU changes. Inspection of Fig. 11 shows some small areas of difference in surface air temperature and precipitation far away from the regions of intense land use, in particular over the oceans. However, the effects of LULCC in these areas cannot be distinguished from natural, internal variability. In the presented analysis we have used averages over 20 years, for which the oceanic variability is not negligible. Therefore, without substantially larger ensembles or longer experiments, we cannot prove causal relationship between T and P changes over the ocean shown in Fig. 11 and land-use changes.

6. Conclusions

In this study we explore effects of LULCC on surface climate on a range of temporal and spatial scales using two ensembles of numerical experiments of the comprehensive GFDL ESM2Mb model. Both sets of experiments use the same historical forcing with two different assumptions about land-use change: the first set with no land-use change (potential vegetation, PV) and the second set with the CMIP5 historical reconstruction LULCC (LU). We apply two different methods to analyze the results of the numerical experiments: 1) we compare the climate from the PV to LU simulations to evaluate the regional and global effects of LULCC, similarly to previous studies (e.g., Chase et al. 2000; Findell et al. 2007; Pitman et al. 2009; Davin and de Noblet-Ducoudré 2010; Jones et al. 2013a,b), and 2) we compare the climate between different land-use type categories within each grid cell in the LU experiment.

Using the first method (i.e., differencing LU and PV ensembles means), the effect of historic LULCC on temperature is found to be mostly regional [similar to Findell et al. (2007) and Pitman et al. (2009)] without strong global effect. However, over the historical period we are able to detect a small but statistically significant global increase of near-surface air temperature due to LULCC. The regional effects are most prominent in North America and Europe in JJA near-surface temperature. Furthermore, our analysis does not support Pitman et al.’s (2009) hypothesis that a fully coupled model could amplify the teleconnections between the regions of intense LULCC and other regions of the world.

Unlike previous studies, we also characterize local climate contrasts due to LULCC by comparing climate states among different land-use tiles within each grid cell in the LU experiment (method 2). Since the atmospheric inputs (e.g., precipitation, downward shortwave radiation, atmospheric temperature) are the same for each tile within a grid cell, the differences among various tiles allow us to isolate changes in the land surface climate due to LULCC from changes induced by climate variability. In computing differences between LU and PV ensembles in method 1, the natural variability from both LU and PV experiments contributes additively to the noise, making signal-to-noise ratio much smaller than in method 2. On the local, subgrid (i.e., tile) scale the signal of the land use is clear and is detectable even if the fraction of the land surface disturbed by the LULCC is small. For example, the cropland–natural subgrid temperature difference signal is detectable with 95% confidence over 68.5% percent of all nonglacier land grid cells in JJA, while in method 1 for the same season the temperature signal is statistically significant only for 8.3% of cells.

In contrast to the LU–PV near-surface temperature differences (method 1), the local signal of LULCC in
near-surface temperature (method 2) is pronounced over majority of areas affected by LULCC with the exception of regions where the physical properties (albedo, roughness, amounts of leaf and roots) of disturbed and undisturbed vegetation are very similar (e.g., pastures and natural grasslands of America and Eurasia). The magnitude of the local signal also tends to be stronger that LU–PV climate difference, roughly by a factor of 1.3 in agricultural areas in tropics throughout the year and 1.5 in extratropics in DJF (Figs. 12 and 13). The largest temperature differences on a subgrid scale are found between croplands and natural vegetation, compared to secondary to natural and pastures to natural differences. This is due to the largest differences in land surface properties induced by land use on croplands. Smaller changes over pasture tiles are explained by the land model assumption that 1) only 25% of biomass on pastures are removed for grazing and 2) pasture could become wooded if environmental conditions permit. A more detailed and region-specific treatment of pastures is needed. It is possible that without more intense pasture grazing, burning, or soil degradation the model underestimates climate contrast of pastures and natural lands in some regions.

For a typical resolution of climate models (e.g., 100–250 km) most of LULCC occur on a subgrid scale and rarely over an entire grid cell. As a result, in LU experiments averaging of managed and natural tiles’ temperature within a grid cell attenuates LULCC effect. On the global scale, the signal of LULCC is further attenuated by averaging temperatures from the regions affected and unaffected by LULCC as well as by combining tropical and extratropical responses, which sometimes offset each other.

We analyze the relationship between the subgrid temperature contrast due to LULCC and regional climate response to LULCC (i.e., LU – PV difference). We find that this relationship is complex and obfuscated by several factors, including climate variability and variations of the properties of the natural vegetation in the regions undergoing LULCC. This implies that the local subgrid-scale temperature effect of LULCC cannot be easily deduced from the regional climate responses. Furthermore, it is the local climate effect that is relevant for assessing impacts of changes in LULCC on functioning of plants, animals, and humans. The importance of local-scale LULCC effect has long been indicated in observationally based studies (e.g., Pielke et al. 2011; Mahmood et al. 2013). Our analysis for the first time demonstrates and quantifies the local LULCC effect in a modeling study with a comprehensive ESM, making it possible to connect the modeling approach with the local observational evidence. This study emphasizes the importance of multiscale approach to characterizing climate changes due to LULCC and land surface heterogeneity it induces.

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