Recognition of climatic effects of land use/land cover change under global warming

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Greenhouse gas emissions and land use/land cover change (LUCC) are two human activities notably affecting climate change. Will temperature and precipitation increase significantly during global warming resulting in more pronounced LUCC climatic effects? Considering the interannual forcing of these two factors, the NCAR Community Atmosphere Model (CAM4.0) was used in this study to investigate the importance of climatological background to LUCC impacts. Experiments based on the difference in the background climate, the greenhouse gas concentrations in 1850 and in the present age indicate contrary changes in climate sensitivity through estimations of the radiative forcing associated with LUCC, which are $0.54^{\circ}\text{C}/(\text{W}/\text{m}^2)$ and $-0.26^{\circ}\text{C}/(\text{W}/\text{m}^2)$, respectively. Therefore, the background climate appears to play an important role in the regional impact of LUCC, especially at higher latitudes. In addition, global warming predominantly influences snow-albedo feedback in the mid-latitudes, thus determining the impact of LUCC, whereas the regional difference in precipitation caused by global warming is responsible for the differing climate response to LUCC in the tropics and subtropics.

land use/land cover change (LUCC), global warming, climatic effects

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Over the past century, global warming has been closely related to human activities [1]. The greenhouse gases in the atmosphere extend far beyond the natural range of the past 65 thousand years. Human-induced greenhouse gas emission is one of the main factors in determining global warming, with the other being land use/land cover change (LUCC). Due to economic and social development, urbanization has accelerated, and croplands have expanded, which has taken place in forests and pastures [2]. Numerical studies have demonstrated that deforestation and desertification can produce noticeable impacts on the regional climate [3–7]. However, studies concerning the effects of LUCC on the climate remain weak, and there have been a lack of systematic evaluations and quantitative conclusions until now [8].

The biogeophysical mechanism of LUCC on the regional

climate influences energy, momentum and the water cycle by modifying the physical properties of the land surface, such as albedo, roughness, and evapotranspiration (ET) [9–14]. While the biogeochemical mechanism of LUCC describes its impact on the carbon cycle [15], almost one-third of the increasing CO_2 in the atmosphere is produced by LUCC [1]. Observational studies suggest that changes in land cover can exert impacts on the local and regional climate [16,17]. Numerical models are also useful tools for LUCC studies. Several studies state that deforestation at low latitudes can lead to a reduction in ET and increases in temperature and CO_2 content, resulting in cooling at higher latitudes of the Northern Hemisphere [18–20]. Swann et al. [21] report a significant warming effect in mid-latitudes due to afforestation. Radiative forcing (RF) has been an effective tool for quantitatively comparing LUCC impact with other influence factors on climate, such as greenhouse gas

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(GHG) emissions [13]. In 2005, the global mean radiative forcing change with respect to 1750 for LUCC and CO₂ were -0.2 ± 0.2 W/m² and 1.66 ± 0.17 W/m², respectively [1]. It is quite obvious that the effect of CO₂ on the global climate is larger than that of LUCC. However, are the effects of LUCC on the regional scale comparable to those of GHG concentrations [22–24]? Pitman and Zhao [25] found that the LUCC impact is of a similar magnitude to that of CO₂ in some boreal regions and that decreasing albedo, resulting from LUCC in high latitudes, contributes significantly to the RF, balancing out or even exceeding the cooling effect due to the changing GHG fluxes [26]. Lee et al. [27] suggest that LUCC produce remarkable impacts on tropical South American precipitation in comparison with SST.

The impacts of LUCC have been compared to the impact of elevated GHGs and the resulting changes in sea surface temperatures and sea ice extent [12]. Voldoire [28] also assessed the impact on the climate of future LUCC relative to the increase in CO₂. However, Pitman et al. [29] noted that the background climate is very important for determining the impact of LUCC on regional climate. Increased GHG-driven changes in snow and precipitation affect the snow-albedo feedback and supply of water, which, in turn, limits evaporation. These changes largely control the net impact of LUCC on regional climate. Thus, studies on the background climate to determine the impact of LUCC require further exploration. However, Pitman et al. [29] used fixed SSTs, land cover and two extreme CO₂ forms (fixed CO₂ concentrations and doubled CO₂ concentrations) in an experimental scheme, which cannot accurately reflect the feedback of the forcing factors. Because interannual evolutions of LUCC actually exist but are rarely considered in model simulations, it is necessary to provide the time evolutions of LUCC in the experimental protocol. In the present study, our aim is to address the robustness of background climate in determining LUCC by considering the time evolutions of climate forcing (e.g. GHG concentrations and LUCC).

1 Model and experimental design

The model used in the present study is the global atmospheric general circulation model of the National Center of Atmospheric Research (NCAR) Community Atmosphere Model, Version 4.0 (CAM4.0) [30]. It can be run together with the land surface model (Community Land Model Version 4.0, CLM4.0), which can provide the energy, momentum and water exchange with CAM4.0 [31]. The finite-volume (FV) dynamical core was selected, and the model was run with $1.9^\circ \times 2.5^\circ$ horizontal resolution and 26 levels in the vertical direction on σ - P coordinate. CAM4.0 and CLM4.0 are the atmosphere and land component models of the Community Earth System Model (CESM), respectively, and have proven to be useful tools for climate simulations

[32–34].

Four 30-year integration experiments were performed (Table 1). The observational monthly SST and sea ice from the Hadley Centre are prescribed during the period of 1971–2000 to drive the model. The experiments include the following: (1) Control run (ctl): Default parameters are used. The GHG concentration is fixed to year 1850 (CO₂ concentration is 284.7 ppm). Land cover type is prescribed with the potential natural vegetation [35], which reflects no significant human activities in 1850. Figure 1(a) presents the main land cover type in each grid in 1850 and shows that the global area weighted average of cropland is 3.28%. Hurtt et al. [36] reconstructed the land use changes from 1700 to 2000 using the Global Land Use Model, which is recommended for CMIP5 model simulations (<http://cmip-pcmdi.llnl.gov/cmip5/forcing.html>). Lawrence et al. [34] put these datasets into NCAR models. Therefore, the time evolution of the land use data in the present study from 1971 to 2000 is based on the work of Lawrence et al. [34]. Figure 1(c) shows the annual time series of the cropland during these periods. (2) Transient experiment (RG): Same as the ctl run, except that the GHG concentrations were prescribed with the annual evolution from 1971 to 2000. Figure 1(d) shows the annual time series for the CO₂ concentrations, indicating a large increase. (3) Transient experiment (RL): Same as the ctl run, except that the time evolution of land use was prescribed from 1971 to 2000. (4) Transient experiment (RGL): the GHG concentrations and land use are all specified with the annual change during the period of 1971–2000. After a spin-up time of 5 years, the last 25-year model's results were used for the analysis. We employed Student's *t*-test to examine the significance of the difference.

2 Results

2.1 Climate sensitivity to LUCC

Radiative forcing (RF) has been the tool utilized for quantitative comparisons of LUCC factor impacts with other influences on climate, such as GHG concentrations; however, the RF of LUCC remains an uncertainty [37]. Davin et al. [38] estimated a climate sensitivity to LUCC, forcing close to $0.52^\circ\text{C}/(\text{W}/\text{m}^2)$, which means that for a change in land cover producing a forcing of $1 \text{ W}/\text{m}^2$, global temperature

Table 1 Experiment and description of climate forcings

Experiment	Description of climate forcings
ctl	GHG concentrations and land cover type are fixed to the year 1850
RG	Same as the ctl but the annual evolutions of the GHG concentrations are prescribed from 1971–2000
RL	Same as ctl but the annual evolutions of land use are prescribed from 1971–2000
RGL	The annual evolution of GHG concentrations and land use are all prescribed from 1971–2000

Figure 1 (a) Main land cover type in 1850; 1, Bare ground; 2, needleleaf evergreen temperate tree; 3, needleleaf evergreen boreal tree; 4, needleleaf deciduous boreal tree; 5, broadleaf evergreen tropical tree; 6, broadleaf evergreen temperate tree; 7, broadleaf deciduous tropical tree; 8, broadleaf deciduous temperate tree; 9, broadleaf deciduous boreal tree; 10, broadleaf evergreen shrub; 11, broadleaf deciduous temperate shrub; 12, broadleaf deciduous boreal shrub; 13, c3 arctic grass; 14, c3 non-arctic grass; 15, c4 grass; 16, crop; 17, wheat; (b) cropland distribution difference between two typical years (2000 minus 1850); (c) time series of global area weighted average cropland; (d) time series for CO₂ concentrations.

will increase by 0.52°C . Climate sensitivity (λ) can be derived from the following ratio:

$$\lambda = \frac{\Delta T}{\Delta F - \Delta R}, \quad (1)$$

where ΔT and ΔF are the surface temperature change and the global mean RF, respectively, and ΔR represents the change in net radiation at the top of the atmosphere. We can obtain different climate sensitivities to LUCC under two background climates derived from four experiments (e.g. RL-ctl; RGL-RG). Based on the greenhouse gas concentrations in 1850 and in the present age (1971–2000), the global

mean surface temperature changes are -0.04 and 0.01°C , and the climate sensitivities are 0.54 and $-0.26^{\circ}\text{C}/(\text{W}/\text{m}^2)$, respectively. Discussing these two background climates in determining the climate sensitivity is the main aim of the present study.

2.2 Spatial features

Figure 2(a) and (b) shows the differences in annual mean surface air temperature, which can be used to quantify the possible impacts of GHG concentrations (RG-ctl) and the effects of LUCC (RL-ctl), respectively. GHG concentrations

Figure 2 Geographic distributions of differences in surface air temperature. (a) RG-ctl; (b) RL-ctl; (c) RGL-ctl. The hollow dots are statistically significant at a 0.05 confidence level.

increase the global surface temperature significantly, whereas LUCC leads to cooling at higher latitudes and warming at lower latitudes.

To explore the importance of background climate in determining the impact of LUCC on regional climate, Figure 3 presents the spatial distribution of surface air differences (RGL-RG) based on the background climate of present GHG concentrations (1971–2000). Compared with the background climate of GHG concentrations in 1850 (Figure 2(b)), surface air temperature due to LUCC shows significant regional differences, especially in North America, Eurasia and India. Based on the zonal distribution of temperature changes (Figure 4), it was found that the surface air temperature increases under the background climate of the GHG concentration in the present age, especially at higher latitudes. A warmer climate can reduce snow depths and positively affect snow-albedo feedback. Meanwhile, global warming will lead to dramatic climate changes, including more rainfall, and evaporation. Together, both effects determine the LUCC impact on regional climate changes.

2.3 Regional analysis

In the transient experiment (RL and RGL), land use is prescribed with the annual evolution during the period of 1971–2000. To illustrate the land use changes due to human activities, Figure 1(b) presents the spatial differences in cropland

Figure 3 Geographic distributions of differences in surface air temperature due to LUCC under current background climate (RGL-RG). The hollow dots are statistically significant at a 0.05 confidence level.

Figure 4 Zonal differences of surface temperature. The solid line indicates the background climate in 1850 (RL-ctl), and the dotted line indicates the present age (RGL-RG).

use in 2000 and 1850. The areas of the cropland use have risen considerably, which have taken the place of forests and pastures, especially in North America, Eurasia, India and East Asia.

At mid-latitudes, such as North America and Eurasia (Table 2), LUCC increase the precipitation and latent heat fluxes under the present background climate. In contrast, warmer climates lead to a reduction in snow and ice, especially during the spring and winter, and then decrease the surface albedo, allowing the surface more access to solar radiation and raising its temperature (Table 2). Therefore, the changes in albedo are more important in determining the impact of LUCC at higher latitudes.

In tropical and subtropical areas (India and East Asia), changes in temperature due to LUCC are region dependent. A warmer climate leads to increases in temperature in East Asia and reductions in India (Table 2). It is well-known that there is a close link between soil hydrological processes and climate change. Soil water can alter the surface albedo and heat content, thus influencing the regional climate. In addition, a strong feedback loop exists between the soil water content and subsequent precipitation [39,40]. Dai [41,42] reported that recent warming could increase rainfall and streamflow, which also appears to have enhanced drying over some land areas. By using the precipitation and streamflow data together with the Palmer Drought Severity Index (PDSI), Dai [41,42] showed a drying trend over most of Africa, South and East Asia, southern Europe, eastern Australia and other regions. The equilibrium of the surface water budget indicates that more precipitation facilitates increases in soil moisture, enhancing surface evaporation and subsequently precipitation. This process eventually induces more latent heat release and a cooling effect. As shown in Table 2, at lower latitudes, the impacts of background climate due to LUCC are generally dominantly controlled by hydrological processes rather than by albedo changes.

3 Conclusions and discussion

Based on numerical experiments using NCAR CAM4.0, the possible causes of background climate in determining the impacts of LUCC on regional climate were investigated in this study. Compared with previous studies, the present experiments consider the annual evolutions of climate forcing (e.g. GHGs and land use). Experiments based on different background climates for the GHG concentrations in 1850 and in the present age indicate that contrary changes in global mean surface temperature are induced by LUCC. In contrast, through estimations of the radiative forcing associated with LUCC in the abovementioned experiments, it was determined that the climate sensitivity is also distinct. Therefore, the background climate appears to play an important role in controlling the net impact of LUCC on the regional climate.

Table 2 Regional differences due to LUCC^{a)}

	Air temperature (°C)		Precipitation (mm)		Latent heat (W/m ²)		Net radiation (W/m ²)		Albedo (×10 ²)	
	1850	Present age	1850	Present age	1850	Present age	1850	Present age	1850	Present age
North America	−0.40	−0.19	−9.24	1.47	−0.98	−0.35	−1.78	−1.23	0.96	0.73
Eurasia	−0.22	−0.02	−3.76	−2.54	−0.43	−0.09	−1.15	−0.73	0.77	0.55
India	0.20	−0.09	−28.71	91.21	−0.89	1.12	−0.64	−1.62	0.22	0.30
East Asia	−0.01	0.04	10.64	−49.25	−0.08	−0.05	−1.39	−0.80	0.53	0.50

a) 1850: RL-ctl; the present age: RGL-RG.

To explore the possible mechanisms due to the background climate on the regional LUCC impacts, four significant regions were selected (Figure 1(b)). It is well-known that the albedo of forests is lower than that of crops. When forests are replaced with crops, especially at high latitudes covered with snow, the surface decreases the absorption of solar radiation significantly. A warmer background climate facilitates a reduction in snow and ice, decreasing the surface albedo and subsequently enhancing the absorption of solar radiation and surface temperature. In contrast, an increase in GHG concentration can lead to a change in rainfall patterns and how net radiation is partitioned between latent heat and sensible heat fluxes (crops have a lower capacity to sustain high latent heat fluxes compared with forests). At higher latitudes, the temperature response due to LUCC is generally dominated by changes in the albedo, whereas, at lower latitudes, changes in soil moisture and rainfall determine the impacts of LUCC, that is, the regional differences in precipitation caused by global warming are responsible for the differing climate responses to LUCC in the tropics and subtropics.

Pitman et al. [29] first proposed the importance of background climate in determining the impacts of LUCC on regional climate. However, these researchers' GCM adopts a fixed SST, land cover change and two extreme cases (pre-industrial CO₂ and doubled CO₂), which ignore the feedback within the climate system. In our transient experiments, the time evolutions of the SST, GHGs and land use have been introduced to represent the relatively true climate forcing factors. Increases in GHG concentrations influence changes in surface albedo and hydrological processes, which determine the impacts of LUCC. Pitman et al. [29] found that doubled CO₂ concentrations can lead to significant rainfall. However, global warming also appears to have enhanced drying over many land areas [41,42]. Therefore, it is necessary to require an accurate simulation of changes in snow cover and rainfall that is geographically coincident with regions of LUCC. Pitman et al. [43] used seven climate models to explore the biogeophysical impacts of LUCC and determined uncertainties among these models. In the present study, it is noted that the climate sensitivity of LUCC may have opposing indications under different background climates. We provide clues for better understanding background climate in determining the LUCC effects on regional

climate. In addition, there are still some limitations and uncertainties. The analysis conducted here includes preliminary findings that require further investigation. For example, the impact of the time evolution of land use changes on regional climate is a problem deserving further study.

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