Biogeophysical impacts of land use/land cover change on 20th century anthropogenic climate compared to the impacts of greenhouse gas change

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Abstract
The accumulated biogeophysical impact of historical land use/land cover change (LUCC) on the 20th century anthropogenic climate is compared to that of greenhouse gas concentration (GHGC) change by examining four experiments with the Community Earth System Model, including a control run, an LUCC run, a GHGC run and a combined anthropogenic run. Globally, the biogeophysical effect of historical LUCC can offset the warming induced by increased GHG. The overall impacts of LUCC and GHGC tend to be linear in their combination. The linearity of the LUCC and GHGC impacts is stronger on the projected temperature than on the projected precipitation. However, the nonlinearity also shows up in some regions where internal variability is strong. It is also found that the precipitation change scaled to the global mean temperature change induced by LUCC is larger than that induced by GHGC due to more effective changes in water vapour content and atmospheric stability. Regionally, LUCC and GHGC have comparable effects on warming over the mid-latitudes of Asia and the mid-low latitudes of the Americas, whereas the LUCC has a pronounced contribution to cooling over high-latitude regions in the Northern Hemisphere (NH). LUCC and GHGC have the largest impacts on surface temperature over the mid-high latitudes, particularly over the NH, through local and remote processes; in contrast, their impacts on precipitation are primarily over tropical regions through teleconnection processes.
results propose that more attention should be paid to the interactions between external forcings and internal variabilities, especially over the regions where nonlinearity is strong, such as Europe, North Africa, southern Australia and northwest North America.

**KEYWORDS**
climate, general circulation model experiments, global, land-atmosphere

1 | INTRODUCTION

World Meteorological Organization has stated that the present warm period (PWP; i.e., the 20th century) is considered an anthropogenic warming period during which temperature changes cannot be solely attributed to natural influences. This warming is a global concern. One response to this concern has been the study of changing surface temperature (TS) caused by anthropogenic and natural phenomena (Tett et al., 2002; Jones et al., 2013). The role of increasing greenhouse gas concentration (GHGC) has been considered a primary cause of present-day global warming (IPCC, 2007; Jones et al., 2013).

Humans have been affecting the climate system mainly in two ways: by modifying the atmospheric composition (such as the emission of greenhouse gases and aerosols) and by changing land surface properties (such as deforestation and urbanization; Shi et al., 2007). The role of increasing greenhouse gas concentration (GHGC) has been considered a primary cause of present-day global warming (IPCC, 2007; Jones et al., 2013).

The role of land use/land cover change (LUCC), however, remains under debate. Over high latitudes, there is a positive vegetation-albedo feedback over northern North America. Initial cooling leads to tundras replacing forests and causes greater cooling because tundras have a higher albedo and reflect more solar radiation. Simulation shows that the loss of boreal forests would provide positive feedback for glaciation (Meissner et al., 2003). Over low latitudes, there is a positive vegetation-rainfall feedback. Initial increased precipitation is helpful for forests replacing grasslands, which leads to the increased transpiration of water vapour and results in additional precipitation. From a biogeophysical point of view, surface warming caused by the low albedo of tropical forests might be offset by strong evaporative cooling. From a biogeochemical point of view, it is not clear whether the potential role of tropical forests would notably help mitigate global warming through the absorption and emission of carbon (Houghton et al., 2015; Mordiyarso et al., 2015). For temperate forests, the effect of the climate is also uncertain. Higher albedo with loss of temperate forests could offset carbon emissions (Snyder et al., 2004), while reduced evapotranspiration with loss of forests could amplify biogeochemical warming. Simulations show that afforestation in northern mid-latitudes warms the Northern Hemisphere (NH) (Swann et al., 2012). Therefore, the net climate impact from tropical, temperate and boreal forests requires further investigation (Bonan, 2008).

Do forest–atmosphere interactions dampen or amplify anthropogenic climate change during the PWP? The contributions of LUCC need to be clarified. Studies have compared the impact of LUCC on climate change with other potential causes, such as increases in CO₂ and solar radiation (Brombik et al., 1999; Lawrence et al., 2018; Chen and Dirmeyer, 2019). These studies found that LUCC and increases in CO₂ have a similar impact on temperature at high latitudes (Pitman and Zhao, 2000), and they have significant radiative effects on global climate (Matthews, 2003). The impact of LUCC on regional hydrometeorology (e.g., North India, southeast China and eastern China, arid and semiarid regions) can also be comparable in magnitude with climate anomalies, such as the El Niño-Southern Oscillation (ENSO) (Findell et al., 2009), and GHGC (Xu and Yang, 2017). However, the global effect of LUCC remains unsettled and is still under investigation (Pielke et al., 2011; Mahmood et al., 2014). Gibbard et al. (2005) found that the global replacement of current vegetation by trees would lead to a global mean warming of 1.3°C, which is nearly 60% of the warming produced under a doubled CO₂ concentration. The warming effect of the presence of trees in their work is due to reduced albedo from a biogeophysical perspective. Arora and Montenegro (2011) suggested that the complete afforestation of an area currently occupied with crops would lead to a reduced warming of approximately 0.45°C. This reduced warming is attributed to the biogeochemical effect. A better understanding of the impacts of LUCC on recent global climate change is clearly needed for the improved prediction of future climate (Mahmood et al., 2010).

To develop a better reality check of the model simulation results, the use of historical LUCC and GHGC changes as forcings to perform sensitive simulations is desirable. However, most works are scenario-based future projections, for example, the Representative Concentration Pathway (RCP) 2.6, RCP4.5, RCP6 and RCP8.5 for the GHGC scenarios (Eichler et al., 2013; Rangwala
et al., 2013; Miao et al., 2014) and the deforestation and afforestation for the LUCC scenarios (Gibbard et al., 2005; Arora and Montenegro, 2011). Thus, the results might be more idealized than realistic.

This work compares the different impacts of transient LUCC and GHGC on temperature and precipitation changes during the PWP using a set of simulations conducted by an earth system model. We are particularly aiming at finding out how LUCC and GHGC interactively affect the global and regional climate and which factor is more effective in changing the global hydrology. The model and experiments are introduced in Section 2. The temperature and precipitation responses are shown in Section 3. The mechanisms of climate change are discussed in Section 4. The conclusions are drawn in Section 5.

2 | MODEL AND EXPERIMENTS

Although there are various experiments carried out by Coupled Model Intercomparison Project Phase 5, including single forcing runs and all forcing runs, they do not, however, contain the combined experiments forced by LUCC and GHGC, which is essential to quantify the contributions of LUCC and GHGC. In this study, four new experiments are designed to evaluate the impacts of human-induced LUCC and GHGC. The Community Earth System Model (CESM), developed by the National Center for Atmospheric Research (NCAR) (http://www.cesm.ucar.edu/models/cesm1.0/), [Hurrell et al., 2013], is used to carry out long-term experiments over the past two millennia. These four experiments consist of one control (CTRL) run; two sensitivity runs, including an LUCC sensitivity run and a GHGC sensitivity run; and one combination run (anthropogenic—ANTH). The boundary conditions set for the two sensitivity experiments are listed in Table 1. The LUCC data set comes from the reconstruction by Kaplan et al. (KK10, Kaplan et al., 2010; Yan et al., 2013). The GHGC data set comes from the reconstruction by Meure et al. (2006).

The CTRL run is carried out under fixed forcings, including fixed solar irradiance (1,360.89 W·m⁻²) and fixed pre-industrial GHGC (Table 1), and the ocean state at 2010 is used as the initial conditions. The CTRL run is continuously run for 2000 model years after 400 years’ spin-up when it reaches the balanced state (Wang et al., 2015). The LUCC run and GHGC run begin in the last year of the CTRL run, with the reconstructed LUCC and GHGC data sets being provided separately and run from 1 AD to 2000 AD. The ANTH run also begins from the last year of the CTRL run, with the combined LUCC and GHGC forcings and runs from 1 AD to 2000 AD. Wang et al. (2015) has evaluated the CTRL run and found that it showed a good performance in simulating the global climate and the internal variabilities, such as the ENSO, the Pacific Decadal Oscillation and the North Atlantic Oscillation (NAO).

Figure 1 illustrates the time series of the human-induced LUCC (crops, C3 and C4 pastures with the dashed lines) fractions and GHGC over the past two millennia. Both LUCC and GHGC change dramatically from 1850 AD to the PWP. On the other hand, LUCC has been found to have long-term impacts on global climate (Yan et al., 2017). Therefore, we will focus on the period of last 100 years, that is, the PWP. The randomly selected ten 100-year periods in CTRL run are averaged and taken as baseline. In this work, impacts on the carbon and nitrogen cycle (CN cycle) are not considered; thus, emissions due to LUCC are excluded for these cycles. Therefore, this work considers only the biogeoophysical effect of the LUCC.

3 | RESULTS

3.1 | Impacts on annual mean TS

3.1.1 | Global mean

Compared to the CTRL run, the PWP-averaged global annual mean TS increases by 0.29°C under GHGC forcing, decreases by 0.12°C under LUCC forcing and increases by 0.17°C under the combined anthropogenic forcing. In this case, the impacts of GHGCs and the biogeoophysical effect of LUCC on global climate change seem to be linear. This might be related to the absence of the CN cycle, which requires further investigation.

The annual mean global temperature increases notably fast after the 1950s under GHGC forcing, while the changes under the LUCC forcing during the 20th century have a slight trend (Figure 2). Warming under the increased GHGC contributes most to the combined ANTH run after the 1950s. On the other hand, LUCC is considerable for mitigating global warming when the GHGC is not that large, for example, during the first half of the PWP.
3.1.2  Latitudinal variation

The zonal mean TS increases obviously in the GHGC run but decreases over mid-high latitudes in the LUCC run (Figure 3). The changes in both simulations are larger over the high latitudes of the NH, and they have an opposite sign with comparable amplitude. The area-averaged TS over the high latitudes of the NH (from 60°N to 90°N) increases by 0.7°C in the GHGC run but decreases by 0.78°C in the LUCC run, resulting in little change in the combined ANTH run (decreased by 0.005°C). The same situation goes for the high latitudes over the Southern Hemisphere (SH) (90°S–60°S). The TS changes little over the mid-low latitudes (30°S–40°N) in the LUCC run; therefore, the change derived from the ANTH run is similar to that from the GHGC run.
run, except that the amplitude is similar to that from the LUCC run.

The change in the zonal mean TS is consistent with the simulated results of Hua and Chen (2013). However, Pitman and Zhao (2000) simulated land cover change that contributed 30–40% to the total warming due to a combination of the land cover change and the change in CO₂ at northern high latitudes. Pitman et al. (2009) explored the impacts of human-induced land cover change using seven climate models and found that the impacts were model-dependent due to different representations of land cover and parameterization. The model used in Hua and Chen (2013) is the NCAR CAM4.0, which is one component of the CESM; therefore, our results are in agreement with theirs. Brovkin et al.’s simulation (Brovkin et al., 1999) also showed notable cooling in the northern mid- and high latitudes in a deforestation scenario using a climate system model of intermediate complexity. The LUCC-induced high-latitude cooling might also be related to the absence of the CN cycle.

The models used in these previous works are either of intermediate complexity or uncoupled, and the results in this work that are similar to the fully coupled earth system model results suggest robust LUCC biogeophysical impacts. The impacts of LUCC and GHGC are opposite and comparable over mid-high latitudes, whereas GHGC dominates over the mid-low latitudes over NH.

### 3.1.3 Global pattern

The effects of GHGC and LUCC result in very different patterns of temperature change. The GHGC-induced warming occurs nearly everywhere, and the largest amplitude is found in the Arctic and over high-latitude land areas in the NH. On the other hand, LUCC induces warming largely over land and complementary cooling over the ocean, especially the Canadian Arctic Ocean (Figure 4).

The TS changes significantly over the Arctic region and its vicinity both in the GHGC run and LUCC run but increases in the GHGC run, while it decreases in the LUCC run. The combined TS in the ANTH run over Europe and
northern Africa shows no significant change (Figure 4b) due to the opposite impacts of GHGC and LUCC. Under the combined GHGC and LUCC effects, the TS increases significantly over Asia, North America, South America, southern Africa, northern Australia, and most ocean areas, while it decreases notably over the oceans surrounding Canada. The striking decrease over northeast North America and Greenland in the LUCC run is consistent with other studies (Pitman et al., 2011; Lawrence et al., 2012).

Although the GHGC has an overall (over 50%) positive contribution to the warming derived from the ANTH run, the biogeophysical impact of LUCC also contributes to warming over tropical Africa, tropical South America, mid-latitude Asia and North America by nearly 50% (Figure S1). For the NH high-latitude cooling in the ANTH run, the LUCC has a positive contribution of over 80% (Figure S1). The contribution is based upon linearity. However, the aforementioned linearity has regional dependence. There is no significant linearity over Europe, North Africa, southern Australia or northwest North America (Figure S2a). Here, the linearity is represented by the sum of the results of the LUCC run and GHGC run divided by the result of the ANTH run.

The poor linearity over Europe, North Africa, southern Australia and northwest North America indicates that we should pay more attention to the interactions between external forcings and internal variabilities over these regions.

3.2 | Annual mean precipitation responses

3.2.1 | Global mean

The biogeophysical effect of LUCC on precipitation is different from that of GHGC. The global annual mean precipitation rate increases by 0.014 mm-day\(^{-1}\) in the GHGC run and decreases by 0.011 mm-day\(^{-1}\) in the LUCC run (Table 2). The LUCC-induced precipitation change per degree of global mean temperature change, which is 3.4%/\(^\circ\)C, is thus greater than that induced by GHGC change (Table 2). The latter is 1.8%/\(^\circ\)C, which is close to the future change under RCP4.5 (approximately 1.9%/\(^\circ\)C; Lee and Wang, 2014). Because the global mean precipitation changes little in the combined ANTH run, the ratio of precipitation change per degree of temperature change is small. The combined effects of LUCC and GHGC also appear to be linear. However, the linearity in the precipitation change is smaller at the regional scale than that in the temperature change (Figure S2b).

3.2.2 | Latitudinal variation

The GHGC and LUCC induce striking latitudinal variations in precipitation. The GHGC tends to increase rainfall over the equatorial region (10\(^\circ\)S–10\(^\circ\)N) and mid-high latitudes in both hemispheres from 40\(^\circ\) to 80\(^\circ\). On the other hand, LUCC generally induces decreased rainfall over the equatorial region between 10\(^\circ\)S and 10\(^\circ\)N, especially south of the equator, but induces increased rainfall between 10\(^\circ\)N and 25\(^\circ\)N. The LUCC also tends to reduce precipitation in mid-high latitudes of the NH (25\(^\circ\)–90\(^\circ\)N) and high latitudes of the SH (50\(^\circ\)–70\(^\circ\)S).

The zonal mean precipitation changes in the ANTH run are a combination of the effects of GHGC and LUCC, particularly the two peaks located near the equator and near 15\(^\circ\)N (Figure 5). The peak near the equator is caused by the strong GHGC effect, while the peak near 15\(^\circ\)N is caused by the strong LUCC effect.

| TABLE 2 | Changes in the global annual mean surface temperature and precipitation rate |
|----------------|-----------------|-----------------|-----------------|-----------------|
| Annual mean | CTRL run | GHGC run – CTRL run | LUCC run – CTRL run | ANTH run – CTRL run |
| Global surface temperature (\(^\circ\)C) | 12.45 | 0.29 | −0.12 | 0.17 |
| Global precipitation rate (mm day\(^{-1}\)) | 2.68 | 0.014 | −0.011 | 0.003 |
| Percentage of precipitation change per degree global mean temperature change (%/\(^\circ\)C) | — | 1.8 | 3.4 | 0.6 |

FIGURE 5 As in Figure 3 but for the precipitation rate differences
by the GHGC. Another peak near 15°N and the adjacent change from 10°N to 40°N can be ascribed to LUCC. The change over the SH is more likely affected by GHGC, especially over the region from 90°S to 30°S, where there is little land. The decreased precipitation over 10°S-EQ in the ANTH run is contributed by the effect of LUCC.

Precipitation increased by 0.032, 0.019 and 0.017 mm·day\(^{-1}\) over 0°–30°N in the ANTH run, the GHGC run and the LUCC run, respectively. As stated above, the increased precipitation in the ANTH run over this region is a combination of the GHGC and LUCC. The decreased precipitation of 0.013 mm·day\(^{-1}\) over 30°S-EQ in the ANTH run is mainly attributed to LUCC, in which precipitation decreased by 0.033 mm·day\(^{-1}\). Precipitation increased by 0.013 mm·day\(^{-1}\) in the GHGC run.

If we look into the zonal mean seasonal precipitation change, we find that the biogeophysical effect of LUCC differs significantly among seasons, while the GHGC does not (not shown). The annual mean decrease in precipitation over 10°S-EQ is attributed to the decrease in boreal winter in the LUCC run. The peak near 20°N is caused by an increase in precipitation in boreal summer. Whether in boreal summer or in boreal winter, the increased precipitation as a response to the GHGC is located near the equator. We argue that tropical precipitation is related to the Intertropical Convergence Zone (ITCZ), which is further north under LUCC forcing than it is under GHGC forcing. In their simulation of the impacts of historical land cover change on boreal winter, Chase et al. (2000) also found that the warming of boreal winter land surfaces due to current vegetation usage allows the ITCZ to occupy its more northerly position. In addition, the seasonal changes of precipitation and temperature induced by LUCC along with the mechanism require further study.

### 3.2.3 Global pattern

In the GHGC run, the precipitation change shows a “wet gets wetter, dry gets drier” pattern over most regions, which is consistent with the future changes under the

![Annual mean precip (PWP)](image)

**FIGURE 6** As in Figure 4 but for the precipitation rate. The blue lines enclose the global monsoon regions which is defined by the areas where the difference between local summer and local winter precipitation rate exceeds 2.5 mm·day\(^{-1}\) and the ratio of local summer precipitation to annual mean precipitation exceeds 0.55 (Wang and Ding, 2008; Yan et al., 2016). The red lines enclose the global arid regions where local summer precipitation rate is below 1 mm·day\(^{-1}\).
RCP 4.5 scenario (Lee and Wang, 2014). On the other hand, in the LUCC run, the biggest change in precipitation occurs over low latitudes. The change in the annual mean precipitation rate shows a “wet gets wetter, dry gets drier” pattern over Eurasia but a “wet gets dry, dry gets wet” pattern over the North American monsoon-desert region and Australian monsoon-desert region. The reduced monsoon rainfall is somewhat consistent with the future changes under the RCP 8.5 scenario (Quesada et al., 2017). The changes over the low latitudes are larger in the LUCC run than those in the GHGC run (Figure 6).

The precipitation change pattern over the low latitudes in the combined ANTH run is similar to that in the LUCC run, especially the “wet west-dry east” patterns over southern Africa, the southern Indian Ocean and South America. A salient feature in the LUCC run is that precipitation is suppressed over the warm pool adjacent to the maritime continent (Figure 6d), which is due to the decreased SSTs in that region (Figure 4d). Suppressed precipitation heating over the central warm pool surrounding the maritime continent tends to generate boundary layer divergent winds that, on the one hand, enhance convergence and precipitation to the north along the latitude belt of 10°N–20°N from South Asia to the central Pacific, resulting in the increased zonal mean precipitation around 15°N, as seen in Figure 6; on the other hand, these winds enhance convergence to the west and east, thereby increasing equatorial precipitation in the western Indian Ocean–Africa and the equatorial central Pacific, resulting in increased zonal mean precipitation near the equator (Figure 5).

The poor linearity in the LUCC and GHGC impacts on precipitation (Figure S2b) suggests more complicated processes than that on temperature and more interactions between the external forcings and internal variabilities.

## Discussion

The surface energy budget is a direct way to explain TS change (Boisier et al., 2012; Xu et al., 2015). In the CESM, the net radiative flux (Figure 7) is calculated by subtracting the net longwave flux at the surface from the net solar flux absorbed by vegetation and the ground.
Similar to the TS changes, the change in the net radiative flux at the surface derived from the combined ANTH run is attributed more to LUCC over land and more to GHGC over oceans. This is particularly true for the sensitive heat flux (Figure S3). The surface radiative flux change explains most of the TS change for East Asia and North America and their adjacent oceans. For cooling over Europe, the local effect might be suppressed by the remote effect through teleconnections.

Hurrell (1996) found that cooling in the northwest Atlantic since the mid-1970s was the result of changes in the NAO. Chase et al. (2001) also suggested that the interaction between LUCC and NAO might be important in explaining climate change. Moreover, the atmospheric general circulation models can reproduce the evolution of the global mean surface air temperature during the 20th century when affected by a combination of changes in sea TS, solar radiation and GHG; however, these changes fail to capture the long-term trend in high-latitude circulation measured by the NAO/Arctic Oscillation or Antarctic Oscillation index, for example, the observed increase in the NAO in the late 20th century (Zhou et al., 2008; Scaife et al., 2009). In our work, the NAO is strengthened when the forcing of LUCC is applied in the simulations. The positive NAO pattern is strengthened in the LUCC run (Figure 8d) and the combined ANTH run (Figure 8b), accompanied by the strengthened 200 hPa westerlies over the mid-high latitude region of the Atlantic (figure not shown) in these two experiments. Therefore, we suggest that LUCC may account for most of the changes in the NAO and thus the changes in temperature over Europe, northwest Atlantic and northeast North America. However, the reason for

![Figure 8](image-url)
the warm pool cooling is not clear and requires further investigation. Note that the strengthened NAO might also be related to the internal variability resulted from model bias, more experiments with more ensemble members are required to confirm the exact effects of LUCC.

The precipitation changes over the eastern region of the maritime continent, which increased in the GHGC run but decreased in the LUCC run, might be related directly to SST changes over this region, which increased in the GHGC run but decreased in the LUCC run (Figure S4). Studies have shown that land cover changes could have an impact on the surrounding oceans through air–sea interactions (Zeng et al., 1996; Delire et al., 2001; Zhao et al., 2001; Voldoire and Royer, 2005). The decreased SSTs over the Indian-Pacific Warm Pool (IPWP) are accompanied by a weakened ascending flow at 500 hPa (not shown) and decreased precipitation over this region in the LUCC run. The increased SSTs in the GHGC run in the IPWP, especially in the eastern Indian Ocean, are accompanied by a strengthened ascending flow at 500 hPa (not shown) over this region and thus increased precipitation.

Over the Asia–Australia regions, the TS is increased over land and decreased over the ocean in the LUCC run, especially over the northern mid-latitudes (Figure 5d). The warmer land and cooler ocean can promote a large-scale sea breeze, as seen in the wind anomaly at 850 hPa between the LUCC run and the CTRL run (Figure S4d), which shows a more northerly displacement of the northern Pacific easterly winds in the LUCC run. This produces strengthened convergence (not shown) over East Asia near 30°N and therefore increased precipitation. The strengthened northern Pacific easterly winds and increased precipitation over the NH tropical region indicate a northward shift in the ITCZ caused by LUCC. The wind anomaly between the GHGC run and the CTRL run shows that the equatorial easterly wind over the western Pacific is strengthened (Figure S4c) and consistent with the increased precipitation over the maritime continent (Figure 6c).

Precipitation is also related to atmospheric static stability and the water vapour content in the atmosphere. Evaporation and specific humidity in the atmosphere increase under GHGC forcing but decrease under LUCC forcing (Figure 9). The water vapour content in the

![annual mean shum850](image)

**FIGURE 9** Annual mean specific humidity at 850 hPa derived from (a) the CTRL run, (b) the difference between the GHGC run and CTRL run, and (c) the difference between Lucc run and CTRL run. Only the grids above the 0.05 confidence level via the t-test are plotted in (b)–(c)
atmosphere increases with increasing temperature according to the Clausius–Clapeyron equation. The atmosphere becomes warmer under the GHGC run, indicating that the water vapour content increases. The atmosphere is more stable under GHGC forcing (Figure 10b), which is consistent with Liu et al.’s work (Liu et al., 2013). Instability also weakens (i.e., the atmosphere becomes more stable) over most NH regions under LUCC forcing (Figure 10c). The increased precipitation over 10°N–20°N (Figure 5) in the LUCC run is caused by the increased moisture (Figure 9c) and the enhanced instability (Figure 10c). The decreased precipitation over 10°S-EQ in the LUCC run is caused more by the decreased moisture (Figure 9c).

Globally, under the GHGC forcing, the increased moisture favours precipitation, while the increased stability does not favour precipitation. Whereas under the LUCC forcing, the decreased moisture and the more stable situation are both disadvantages for precipitation. This makes the precipitation change per degree of temperature change to be smaller under the GHGC forcing than under the LUCC forcing.

Finally, to test the robustness of the biogeophysical impacts of LUCC, we conducted additional ensemble experiments with four members forced by the same historical LUCC. The changes in the ensemble mean TS and precipitation (Figure S5) are similar to those in the single run we have presented (Figure 4d and Figure 6d). This is because we are looking at the PWP-averaged departure from the results of the CTRL run; therefore, the internal variability has little impact.

CONCLUSIONS

Four experiments are used to investigate the accumulated biogeophysical effects of LUCC on 20th century anthropogenic climate change comparing to the effects of GHGC. Our results indicate that the statistically significant biogeophysical impact of historical LUCC is comparable in overall magnitude to that of historical GHGC, especially over mid-high latitudes, both of which contribute to anthropogenic climate change during the PWP. More importantly, the cooling effect of
LUCC over Nordic seas can suppress the warming effect of GHGC. The biogeophysical effects of LUCC and the effects of GHGC might be linear at the global scale, and this linearity is stronger in the temperature change than it is in the precipitation change. The linearity in the LUCC and GHGC impacts on temperature has regional dependence, which is not significant over Europe, North Africa, southern Australia and northwest North America. Nonlinearity suggests that we should pay more attention to the interactions between external forcings and internal variabilities when investigating the climate effects of external forcings either for the past or for the future projection.

LUCC changes precipitation more effectively than GHGC. The stabilities become stronger both in the GHGC and LUCC runs, but the moisture changes differently in these two runs: increased in the GHGC run but decreased in the LUCC run. This makes the precipitation per degree of temperature change being larger in the LUCC-forced run than in the GHGC-forced run. In addition, the LUCC and GHGC have notable opposite impacts on the zonal distribution of precipitation. We also note that precipitation over the warm pool adjacent to the maritime continent is suppressed due to the decreased SST in the LUCC run, which is noteworthy and need further investigations.

This study focuses on the biogeophysical effects of LUCC, more sensitivity runs, including biogeochemical effects, are required to better understand the actual impacts of LUCC on global climate change.

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