



Impacts of land use and land cover changes on compound dry and hot extremes over Northern hemisphere

Pinya Wang^{1,2,3} · Yuanlin Zheng^{1,2} · Mengyun Li^{1,2} · Yu Song^{1,2} · Yang Yang^{1,2} · Jianping Tang⁴ · Hong Liao^{1,2}

Received: 19 October 2025 / Accepted: 26 May 2026 / Published online: 15 June 2026
© The Author(s), under exclusive licence to Springer-Verlag GmbH Germany, part of Springer Nature 2026

Abstract

Land use and land cover changes (LULCC) since industrialization have significantly altered precipitation and temperatures across Northern Hemisphere continents, and thus the occurrences of compound dry and hot extremes (CDHEs). Here, we employ five model pairs from the CMIP6 Land Use Model Intercomparison Project (LUMIP) to isolate the biogeophysical effects of LULCC over 1980–2014 on summer (June–August) CDHEs over North America (NA), Europe (EU), and China (CN), quantifying changes in CDHE occurrence, intensity, duration, and frequency. Multi-model ensemble means indicate that LULCC reduces CDHE occurrence and cumulative days by 0.1–0.5 events yr⁻¹ and 0.4–1.2 days yr⁻¹ in NA and EU, whereas it enhances these metrics by up to 0.1 events yr⁻¹ and 0.6 days yr⁻¹ in CN, with intensity and duration exhibiting considerable spatial heterogeneity. Mechanistic analyses reveal that these contrasting responses are shaped by both local biogeophysical feedbacks and non-local atmospheric circulation adjustments. Locally, LULCC-induced shifts in sensible and latent heat flux partitioning and evapotranspiration dominate the surface energy redistribution, outweighing radiative forcing effects. At the large scale, LULCC drives an anomalous anticyclonic circulation and moisture divergence over CN, but anomalous cyclonic patterns and enhanced moisture convergence over NA and EU. These results demonstrate that LULCC plays a critical role in shaping compound extreme risks through coupled local and non-local pathways, underscoring the need for improved representation of land–atmosphere interactions in Earth system models.

Keywords Compound dry and hot extremes · Land use and land cover change · Land use model intercomparison project · Biogeophysical effects

1 Introduction

Under global warming, extreme climate events such as extreme heat and drought have received significant attention due to their devastating socioeconomic impacts (e.g., Campbell et al. 2018; Perkins-Kirkpatrick et al. 2020). Numerous studies have demonstrated that there is a positive interaction between extreme heat events and droughts. Specifically, drought reduces soil moisture content, which suppresses evapotranspiration. This leads to decreased latent heat flux and enhanced sensible heating, thereby intensifying extreme heat events (Miralles et al. 2012). Meanwhile, elevated temperatures can accelerate the evaporation of soil moisture, further intensifying the aridity (Seneviratne et al. 2010; Zhou et al. 2020; Alessi et al. 2022). The positive feedback mechanism between hot extremes and droughts thus contributes to the frequent occurrence of compound dry and hot extremes (CDHEs), which refer to periods when extreme high temperatures and drought occur

✉ Yang Yang
yang.yang@nuist.edu.cn

¹ State Key Laboratory of Climate System Prediction and Risk Management, Jiangsu Key Laboratory of Atmospheric Environment Monitoring and Pollution Control/Jiangsu Collaborative Innovation Center of Atmospheric Environment and Equipment Technology, Joint International Research Laboratory of Climate and Environment Change, Nanjing University of Information Science and Technology, Nanjing, Jiangsu, China

² School of Environmental Science and Engineering, Nanjing University of Information Science and Technology, Nanjing, Jiangsu, China

³ State Key Laboratory of Atmospheric Environment and Extreme Meteorology, Beijing, China

⁴ School of Atmospheric Sciences, Nanjing University, Nanjing, Jiangsu, China

simultaneously. Particularly, such compound extremes generally cause amplified impacts than the single extreme heat or drought event (Leonard et al. 2014). CDHEs have become more frequent and intense in recent decades and are expected to continue this trend in the future (Tang et al. 2022; Ye et al. 2025).

While numerous studies have examined the effects of climate warming on the frequency and intensity of CDHEs (e.g., Zeng et al. 2024; Cheng et al. 2019), the role of land use and land cover changes (LULCC) in shaping CDHEs has received limited attention. Since the industrialization, land use and land cover have undergone substantial transformations (Ramankutty et al. 2006), profoundly altering regional climate through biogeophysical and biogeochemical processes (Findell et al. 2007, 2017; Pitman et al. 2009; Mahmood et al. 2014). The biogeophysical processes refer to changes in physical processes such as albedo, evapotranspiration, and the surface energy balance induced by LULCC (Pielke et al. 1998; Lee et al. 2011; Mahmood et al. 2014), while the biogeochemical effects involve LULCC-induced changes in the carbon and nitrogen cycles, greenhouse gas emissions, and aerosol formation (Pongratz et al. 2010; Bright et al. 2015).

A growing body of literature has assessed the impacts of LULCC on climate variables and extreme indices (e.g., Pielke et al. 1998, 2011; Brovkin et al. 2013; Pongratz et al. 2021; Miralles et al. 2025). Through the Land-Use and Climate, Identification of Robust Impact (LUCID) project multi-model experiments, De Noblet-Ducoudré et al. (2012) found that historical LULCC led to an increase in surface albedo over North America and Eurasia, resulting in a regional cooling effect. However, model responses to LULCC vary considerably due to differences in model design and physical parameterization (Findell et al. 2007; Pitman et al. 2009). For instance, Findell et al. (2007) identified considerable inter-model disagreement in the biogeophysical responses to replacing mid-latitude forests with grasslands or croplands. Models that emphasize the increased albedo associated with deforestation tend to simulate reduced net radiation at the surface, as more incoming solar radiation is reflected. This reduction in available energy limits surface heating, thereby offsetting or even reversing temperature increase. Such mechanism is supported by observational evidence particularly in high-latitude regions where albedo effect of deforestation dominates over evapotranspiration-driven warming, resulting in a net local cooling response (Lee et al. 2011). In contrast, models that emphasize the hydrologic impact of reduced rooting depths tend to have less water available for evapotranspiration, weakening evaporative cooling and leading to surface warming. Despite these inter-model uncertainties, there is broad consensus that LULCC exerts negligible effects on

global mean climate but produces significant responses at the regional scale (Findell et al. 2007; De Noblet-Ducoudré et al. 2012).

Regarding the impacts of LULCC on climate extremes, Pitman et al. (2012) found that LULCC from 1870 to 1992 had led to a cooling trend in the mid-latitudes of North America and Eurasia, resulting in a decrease in warm days (TX90p) and warm nights (TN90p), and an increase in cold days (TX10p) and cold nights (TN10p), while in tropical regions some local warming occurred due to changes in evapotranspiration and surface roughness. Building on this, Findell et al. (2017) demonstrated that the conversion of mid-latitude natural forests to croplands and pastures during 1981–2005 suppressed latent heat flux and enhanced sensible heat flux, significantly increasing the frequency of hot-dry summers. Seneviratne et al. (2018) further emphasized that land–atmosphere feedbacks mediated through soil moisture and land-use forcing play a major role in shaping projected changes in extremes under 1.5 °C warming, particularly in densely populated regions of North America, Europe, and Asia. However, most previous work has focused on the effects of LULCC on individual climate variables or single-variable extreme indices, whereas the impacts of LULCC on CDHEs remain largely unexplored, underscoring the need for a systematic assessment.

This study utilizes simulations from the Coupled Model Intercomparison Project Phase 6 (CMIP6) Land Use Model Intercomparison Project (LUMIP) to assess the impacts of land use and land cover change (LULCC) on CDHEs. The LUMIP framework is designed to isolate the climatic effects of LULCC, while CMIP6 incorporates updated and more accurate land-use data. Here, we solely examine the biogeophysical effects of LULCC (see Sect. 2). Specifically, we analyze the cumulative effects of LULCC from 1980 to 2014 relative to the pre-industrial period on various characteristics of CDHEs across the Northern Hemisphere during summer (June–August), with a particular focus on three densely populated and economically developed regions: North America (NA), Europe (EU), and China (CN). Furthermore, we interpret the driving mechanisms behind the evolution of CDHEs by dissecting LULCC-induced changes in key physical factors.

2 Data and methods

2.1 CMIP6 data and experimental designs

In this study, we utilize five CMIP6-LUMIP global climate models (GCMs; Table 1). These models were selected because they are the only ones that provided all required variables for both the Historical and Hist-noLu experiments

Table 1 Information for the five adopted models from LUMIP

Model	Institution/Nation	Resolution	Dynamic vegetation	Number of plant functional types (PFT)
ACCESS-ESM1-5	CSIRO/Australia	145 × 192	No	9
CMCC-ESM2	CMCC/Italy	192 × 288	Yes	16
CNRM-ESM2-1	CNRM-CERFACS/France	128 × 256	Yes	9
MPI-ESM1-2-LR	MPI-M/Germany	96 × 192	Yes	12
MIROC-ES2L	MIROC/Japan	64 × 128	Yes	13

Table 2 Reclassified five land types according to LUH2

Label	Land use type in LUH2
Cropland	C3 annual crops + C3 perennial crops + C4 annual crops + C4 perennial crops + C3 nitrogen-fixing crops
Forest	Forested primary land + potentially forested secondary land
Non-forest	Non-forested primary land + potentially non-forested secondary land
Grazing land	Managed pasture + rangeland
Urban land	Urban land

under the CMIP6-LUMIP framework at the time of this analysis, and have been demonstrated to perform well in reproducing present-day climatological features (Zhang et al. 2024a). Among the five models, CMCC-ESM2, CNRM-ESM2-1, MPI-ESM1-2-LR, and MIROC-ES2L incorporate a dynamic global vegetation model (DGVM), while ACCESS-ESM1-5 does not employ an interactive DGVM in the LUMIP experiments used here (Hong et al. 2022; Hajima et al. 2020). Employing these five models to construct a multi-model ensemble enables a more robust characterization of structural uncertainties in land–atmosphere interactions, consistent with the recommended practice of LUMIP multi-model intercomparison studies (e.g., Lawrence et al. 2016). “Historical” experiment is a fully coupled simulation from 1850 to 2014, which contains all natural (e.g., volcanic aerosols and solar variability) and anthropogenic (e.g., GHGs, aerosols, and LULCC) forcings. The “Hist-noLu” experiment is the same as “Historical” experiment, but with LULCC fixed at the 1850 level (Ge et al. 2022; Lawrence et al. 2016). Furthermore, the “Hist-noLu” experiment maintains the same CO₂ concentration as the “Historical” experiment (Liu et al. 2022; Luo et al. 2022). Therefore, “Historical” experiment minus “Hist-noLu” experiment can isolate biogeophysical effects of LULCC on climate (Zhang et al. 2024a, b; Luo et al. 2024; Tang et al. 2025).

We employ ten variables from these both “Historical” and “Hist-noLu” experiments for the period 1980–2014, including daily maximum temperature (T_{max}), precipitation (Pr), monthly sensible heat flux (SH), latent heat flux (LH), surface upwelling longwave radiation, surface downwelling longwave radiation, surface upwelling shortwave

radiation, surface downwelling shortwave radiation, evapotranspiration (ET), total soil moisture content (SM) and leaf area index (LAI). Note that surface net radiation (NR) is calculated as net downwelling shortwave (downward minus upward) plus net downwelling longwave (downward minus upward). Although LH is physically proportional to ET, they are presented separately here to distinguish between energy flux and water flux perspectives. To investigate the large-scale atmospheric circulation responses to LULCC, we additionally utilize monthly 500 hPa geopotential height (Z500) and horizontal wind fields (U500, V500). Vertically integrated moisture flux (IVT) and its divergence are computed by integrating specific humidity and horizontal wind throughout the atmospheric column. All model outputs are regridded into a uniform spatial resolution of 1° × 1° using bilinear interpolation.

2.2 Land-use harmonization data

Land-Use Harmonization 2 (LUH2) is a global land use and land cover change dataset specifically designed to support Earth system models and climate change research. It is an improvement over Land-Use Harmonization 1 (LUH1), aiming to provide more accurate and detailed historical evolution and future simulations of global land use (Hurtt et al. 2020). LUH2 provides long-term trends in land use changes from 850 to 2100, with a spatial resolution of 0.25° × 0.25°. It includes 12 types of land use which are reclassified into 5 land use types as in Zhang et al. (2024a) (see Table 2). Specifically, forest refers to the combination of primary and secondary forests, while non-forest refers to the combination of primary and secondary non-forests, and cropland is an aggregation of five crop types, and grazing land includes managed and unmanaged pastures. The dataset also includes land use management layers, such as wood harvest, irrigation, and nitrogen fertilizer application (Hurtt et al. 2020).

2.3 Identification of compound dry and hot extreme events

Various approaches have been proposed to define CDHEs, including the copula-based joint distribution method (Tavakoli et al. 2020) and local percentile-based thresholds (Wang

et al. 2017; Yang et al. 2023). In this study, we adopted the latter approach due to its simplicity and widespread application in identifying extreme weather events. Specifically, we define an extreme dry and hot day as a day when a daily T_{max} exceeds the 85th percentile of the summer daily T_{max} ($T_{max} \geq T_{max_{85}}$) and the daily Pr is below the 15th percentile of the summer daily Pr ($Pr \leq Pr_{15}$) simultaneously, and a compound dry and hot extreme event consists of at least three consecutive extreme hot and dry days, with both thresholds calculated for each grid cell and each calendar day based on all summer (June–August) days during 1980–2014 (e.g., Feng et al. 2023; Ye et al. 2025). Moreover, three threshold combinations are tested for the identification of a CHDE, i.e., $T_{max} \geq T_{max_{75}} \cap Pr \leq Pr_{25}$, $T_{max} \geq T_{max_{85}} \cap Pr \leq Pr_{15}$, and $T_{max} \geq T_{max_{90}} \cap Pr \leq Pr_{10}$. Sensitivity analysis shows that despite varying absolute CDHE occurrence across definitions, the spatial patterns of CDHE relative changes induced by historical LULCC and change directions in key regions remain highly consistent (see Supplementary Figs. S1, S2). Accordingly, the moderate threshold ($T_{max} \geq T_{max_{85}} \cap Pr \leq 15$ th) was selected for the main analysis. For a comprehensive understanding of how CDHEs respond to LULCC, we focus on various characteristics of CDHEs including their occurrences, intensity, duration, and frequency within a given period. For a specific year, the occurrences of CDHEs refers to the number of CDHEs within the year. The intensity of CDHEs refers to the average of the highest temperature during CDHEs. The duration of CDHEs refers to the average episodes of CDHEs within a year. The frequency of CDHEs refers to the cumulative count of dry and hot days within the year (Ye

et al. 2025). Note that, we focus on all CDHEs in summer months (June–August) from 1980 to 2014.

3 Results

3.1 Land cover and land use for historical and pre-industrial period

Figure 1 shows the spatial magnitude of different type of LULCC averaged over the period 1980–2014 relative to 1850 and the series of the Northern Hemisphere (NH) land area fractions for each land use type in 1850–2014. Historical LULCC over NH has been mainly characterized by the reduction of forest and non-forest land (Fig. 1a), as well as the increase in cropland, grazing land and urban (Fig. 1b). The time series of fraction of different land types over since 1850 has been primarily characterized by a reduction in forest and non-forest, alongside an increase in cropland and grazing land, with a slight expansion of urban (Fig. 1c). Specially, the combined area of forest and non-forest in the Northern Hemisphere had decreased by 14.8% in 2014 relative to that in 1850, with forest area declining by 2.9% and non-forest area by 11.9%. Meanwhile, cropland increased by 5.6%, grazing land by 8.9%, and urban areas by 0.3%.

Particularly, the three densely populated and high urbanized regions including NA, EU, and CN are selected as key regions for the associated mechanism analysis. The influence of CDHEs tends to be strongly amplified in these regions due to high population density and rapid socioeconomic development, thereby leading to elevated health risks

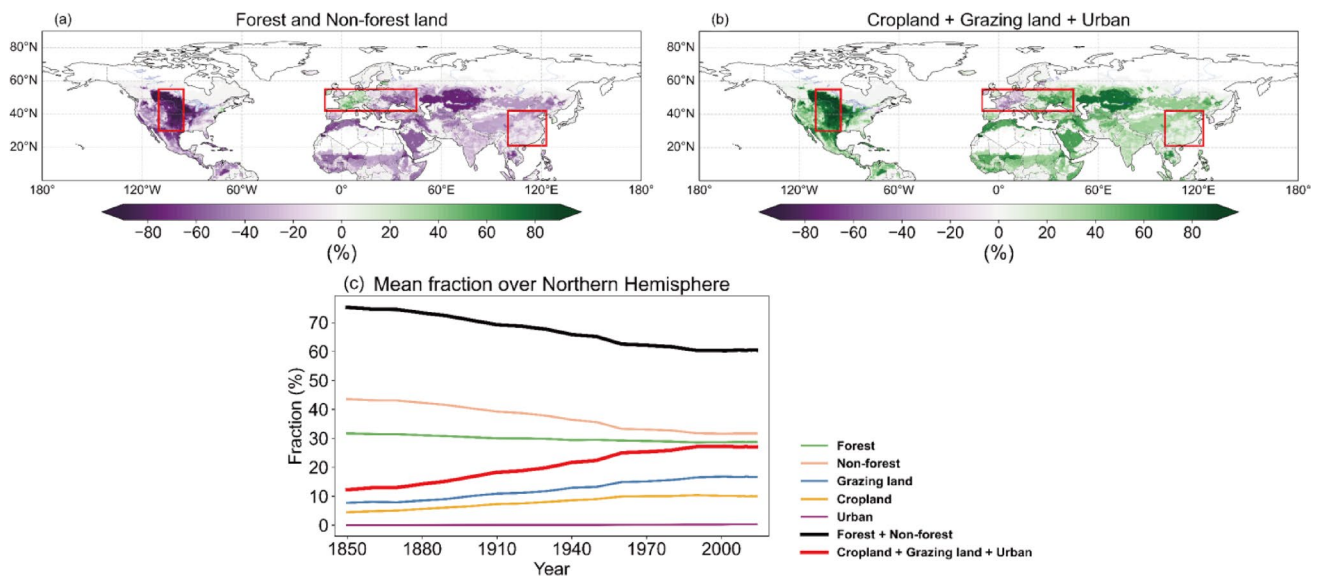


Fig. 1 Historical land use and land cover change. **a** Spatial changes in forest and non-forest land cover averaged for 1980–2014 relative to 1850, **b** same as **a**, but for the combined changes of cropland, grazing land, and urban land. **c** Time series of land area fractions averaged

over the Northern Hemisphere for each land use type during 1850–2014. The red boxes highlight three study regions: North America (NA; 30–55°N, 95–110°W), Europe (EU; 42–55°N, 10°W–45°E), and China (CN; 21–42°N, 100–123°E)

and greater economic damage (Cheng et al. 2025). Figure 2 further illustrates the fractions of each land cover type in the three regions for the present-day and the pre-industrial period, respectively. Compared to 1850 levels, the areas of non-forest and forest regions in NA, decrease by 60.6% and 4.02%, respectively, during 1980–2014, while grazing land, cropland, and urban areas increase by 33.7%, 30.66%, and 0.27% respectively. In EU, the area of non-forest regions decreases by 15.92%, whereas the urban, cropland, grazing land and forest areas increase by 1.11%, 13.29%, 0.6%, and 0.73%, respectively. In CN, non-forest and forest areas decrease by 12.43% and 6.18%, respectively, while grazing land, cropland, and urban areas increase by 13.01%, 4.94%, and 0.65%.

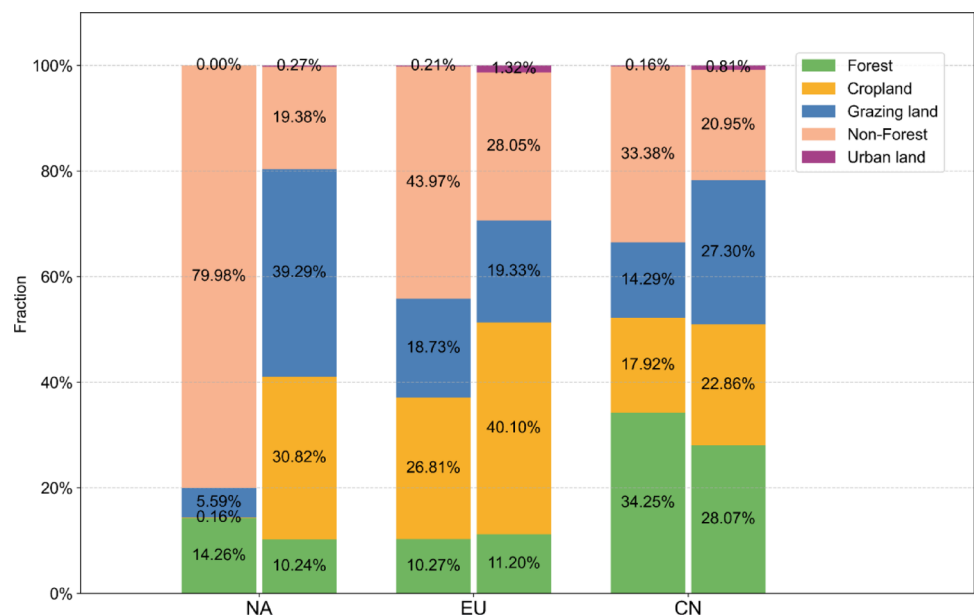
3.2 The effects of LULCC on summer mean temperature and precipitation

Before assessing the LULCC effects on CDHEs, we first examine its impacts on maximum temperature and precipitation during summer season. Figure 3 exhibits the spatial distributions of LULCC effects on the average of daily T_{max} in summer months of 1980–2014 (“Historical” minus “Hist-noLu”). It is noted that the effects of LULCC on temperatures exhibit significant discrepancies among different climate models, consistent with recent evaluation works, which have demonstrated that models respond differently when simulating the effects of forest cover changes on surface properties (e.g., albedo), sensible and latent heat fluxes, and consequently, temperature (Ge et al. 2021; Luo et al. 2023). The inter-model uncertainty arises from differences in model design and physical parameterization (Pitman et al. 2009; De Noblet-Ducoudré et al. 2012). Therefore, we

consider both the multi-model ensemble mean and the individual model outputs to comprehensively and accurately characterize the effects of LULCC, with special focus on the three key regions. Regarding the LULCC-induced changes in T_{max} in NA, three out of the five models (CNRM-ESM2-1, CMCC-ESM2, and MIROC-ES2L) show a predominance of cooling (Figs. 3b–d). ACCESS-ESM1-5 indicates warming in the northern part and cooling in the south (Fig. 3a). MPI-ESM1-2-LR shows cooling in the west part and an increase in the eastern part (Fig. 3e). The multi-model ensemble (MME) shows a cooling effect across most of NA (Fig. 3f), with the maximum cooling exceeding 0.4°C . Over the EU region, the differences among different climate models are more pronounced. ACCESS-ESM1-5 and CNRM-ESM2-1 both indicate warming in western EU and cooling in the east (Figs. 3a–b). CMCC-ESM2 simulates cooling throughout the entire region (Fig. 3c). MIROC-ES2L shows a cooling in the northern part and a slight warming in a small southern area (Fig. 3d). MPI-ESM1-2-LR depicts a cooling in the western part and a warming in the eastern part (Fig. 3e). The MME shows a decrease throughout the EU (Fig. 3f), with the maximum cooling exceeding 0.4°C . In CN, three out of the five models (ACCESS-ESM1-5, CNRM-ESM2-1, MPI-ESM1-2-LR) show widespread warming (Fig. 3a–b and e), whereas CMCC-ESM2 and MIROC-ES2L exhibit cooling over most regions (Figs. 3c–d). The MME shows general warming across CN and a slight cooling in the southeastern region (Fig. 3f). The maximum warming exceeds 0.3°C , and the maximum cooling exceeds 0.1°C .

Figure 4 demonstrates the effects of LULCC on summer mean Pr. For NA, three out of the five models (ACCESS-ESM1-5, CNRM-ESM2-1, CMCC-ESM2) show increased Pr across most regions (Figs. 4a–c). MIROC-ES2L shows an

Fig. 2 Proportion of land cover types across the three selected regions (NA, EU, and CN) for the pre-industrialization and present-day periods. For each region, the left and right bars represent the land cover composition in 1850 and the corresponding average during 1980–2014, respectively



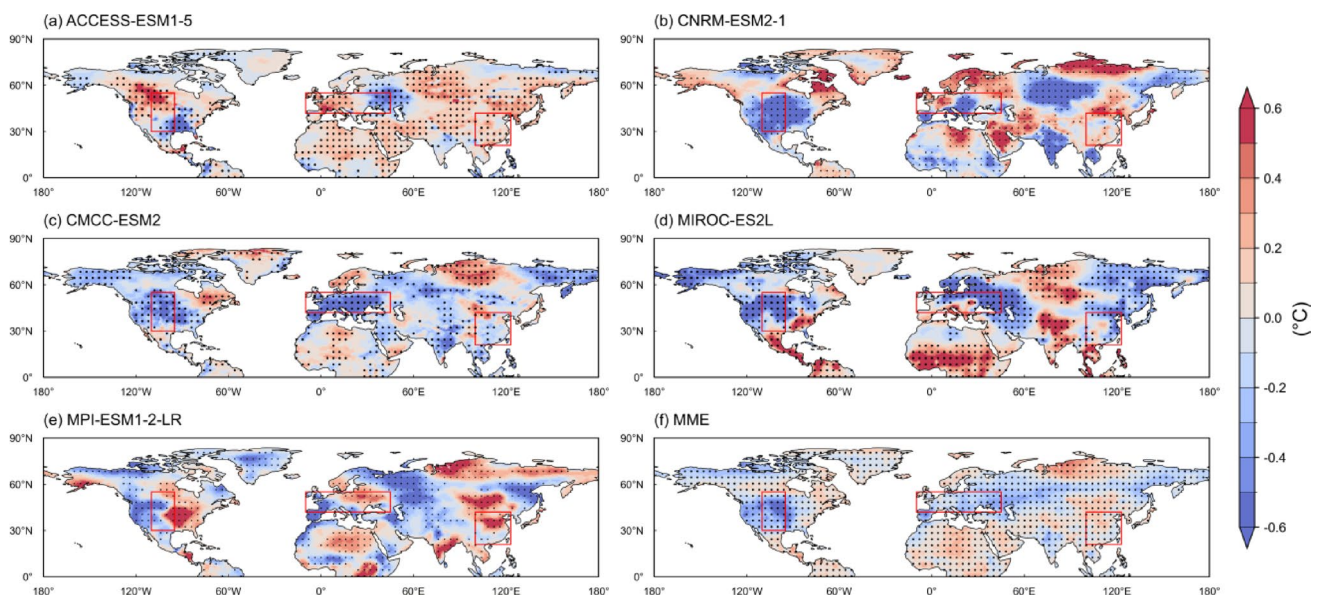


Fig. 3 Spatial patterns of LULCC-induced changes in summer mean daily maximum temperature (T_{max}) during 1980–2014 for individual models and the multi-model ensemble (MME). Panels (a–e) show results from the five CMIP6 models, and panel f shows the MME

result. Red boxes denote the three study regions: NA, EU, and CN. Stippling indicates regions where at least three out of five models agree on the sign of the change (Historical minus Hist-noLu)

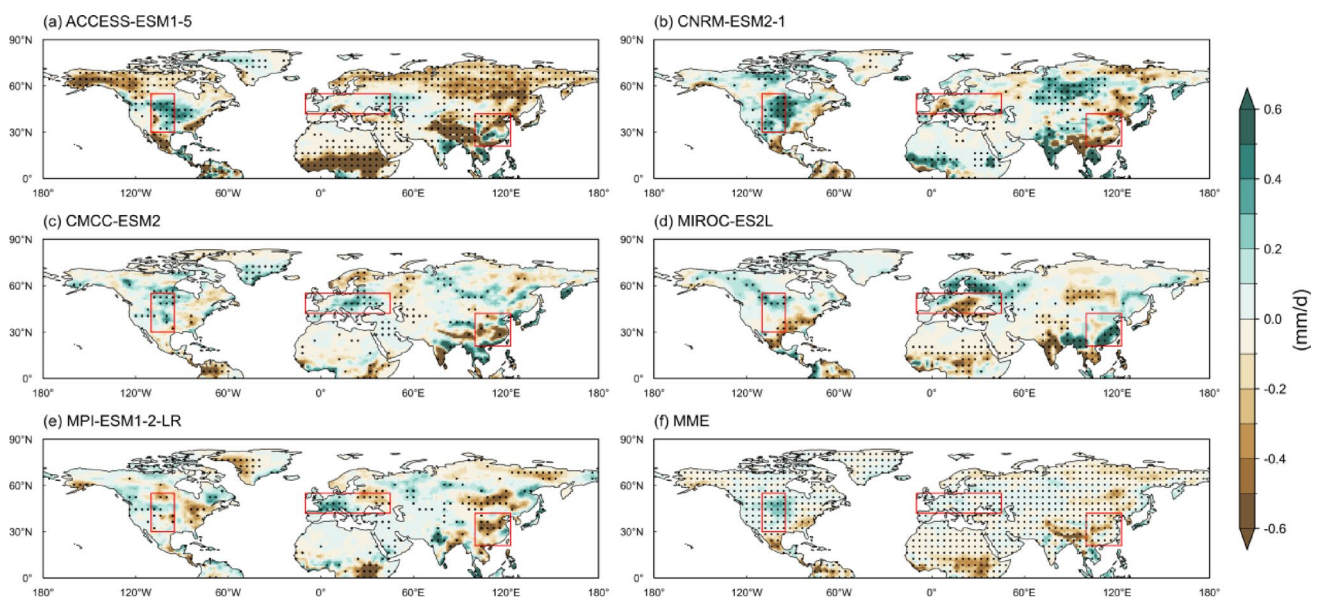


Fig. 4 The same as Fig. 3, but for LULCC-induced changes in summer mean precipitation (Pr) during 1980–2014

increase in Pr in the northern part and a slight decrease in the southern part (Fig. 4d). MPI-ESM1-2-LR shows decreased Pr in parts of the northern and central regions, with the rest showing increased Pr (Fig. 4e). Overall, the MME shows an increase in Pr in most regions of NA (Fig. 4f), with the maximum increase exceeding 0.4 mm/d. In the EU, three out of the five models (ACCESS-ESM1-5, CNRM-ESM2-1, CMCC-ESM2) also show widespread increases in Pr (Figs. 4a–c). MIROC-ES2L shows a decrease across most regions, with a slight increase in the northern part (Fig. 4d).

MPI-ESM1-2-LR indicates increased Pr in the western and decreased Pr in the east (Fig. 4e). The MME shows an increase in most regions of the EU (Fig. 4f), with the maximum increase exceeding 0.4 mm/d. In CN, four out of the five models show increased Pr across most regions, while only MPI-ESM1-2-LR shows a decrease in most regions. The MME shows a decrease in Pr in most regions of CN (Fig. 4f), with the maximum decrease exceeding 0.4 mm/d.

The inter-model discrepancies in the simulated T_{max} and Pr responses to LULCC are consistent with those reported

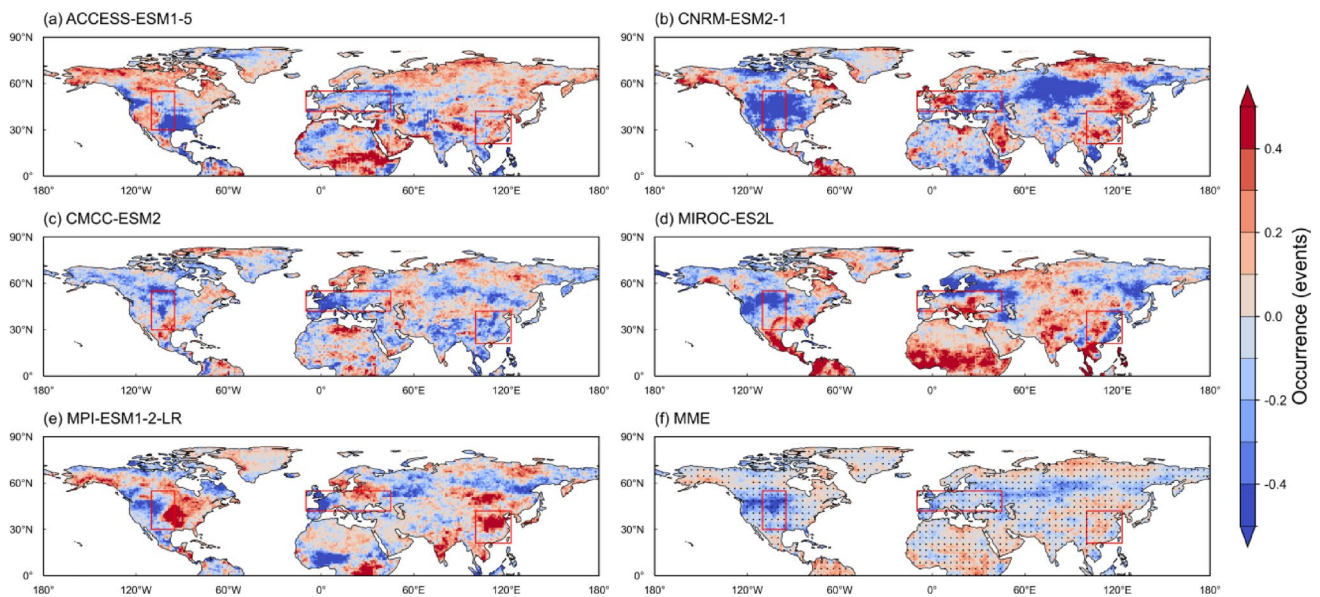


Fig. 5 The same as Fig. 3, but for LULCC-induced changes in the occurrence of CDHEs during 1980–2014

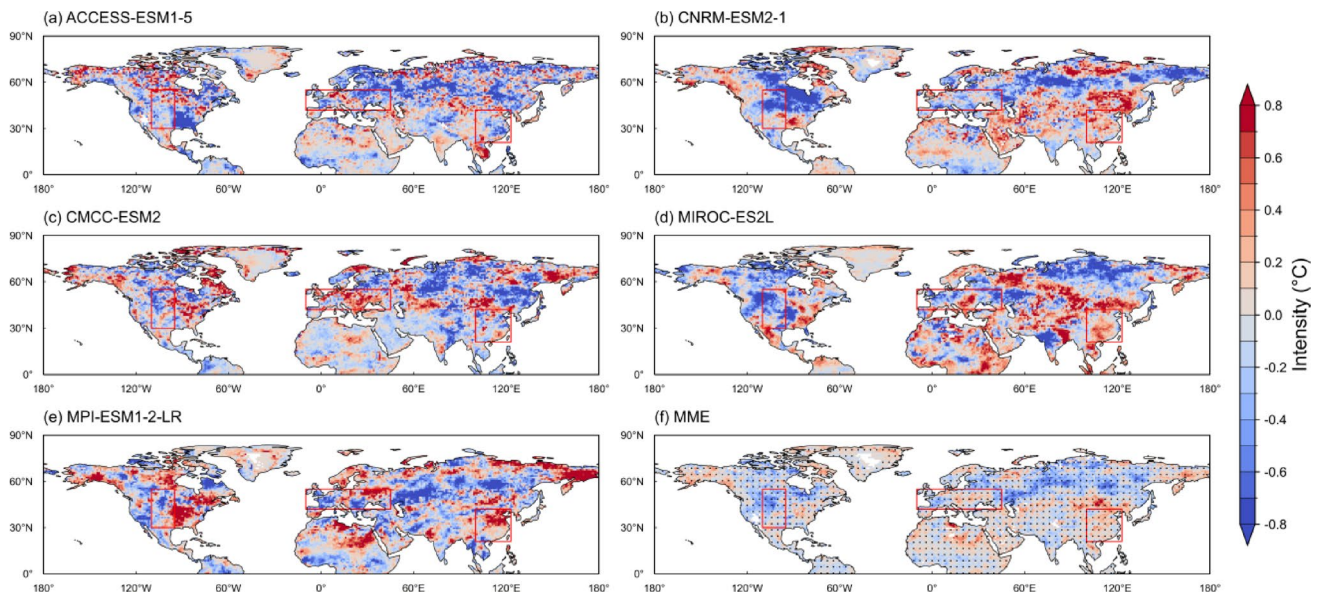


Fig. 6 The same as Fig. 3, but for LULCC-induced changes in the intensity of CDHEs during 1980–2014

in previous studies (De Noblet-Ducoudré et al. 2012; Ge et al. 2021; Luo et al. 2023), and reflect the inherent structural uncertainties in how different models represent key land–atmosphere processes such as surface albedo, evapotranspiration, and sensible–latent heat flux partitioning (Pitman et al. 2009; Boisier et al. 2012). Despite these inter-model uncertainties, the MME results provide a physically consistent picture of the LULCC-induced changes in T_{max} and P_r across the three study regions, forming the basis for the subsequent analysis of CDHE responses in Sect. 3.3.

3.3 The effects of LULCC on different characteristics of CDHEs

In this section, we analyze the impacts of LULCC on various characteristics of CDHEs, including their occurrence, intensity, duration, and frequency, as shown in Figs. 5, 6, 7 and 8. Regarding the LULCC effects on the occurrence of CDHEs, in NA, three out of the five models (CNRM-ESM2-1, CMCC-ESM2, MIROC-ES2L) show a widespread decrease (Figs. 5b–d). ACCESS-ESM1-5 shows a decrease in the southeastern part and a slight increase elsewhere (Fig. 5a), while MPI-ESM1-2-LR exhibits a

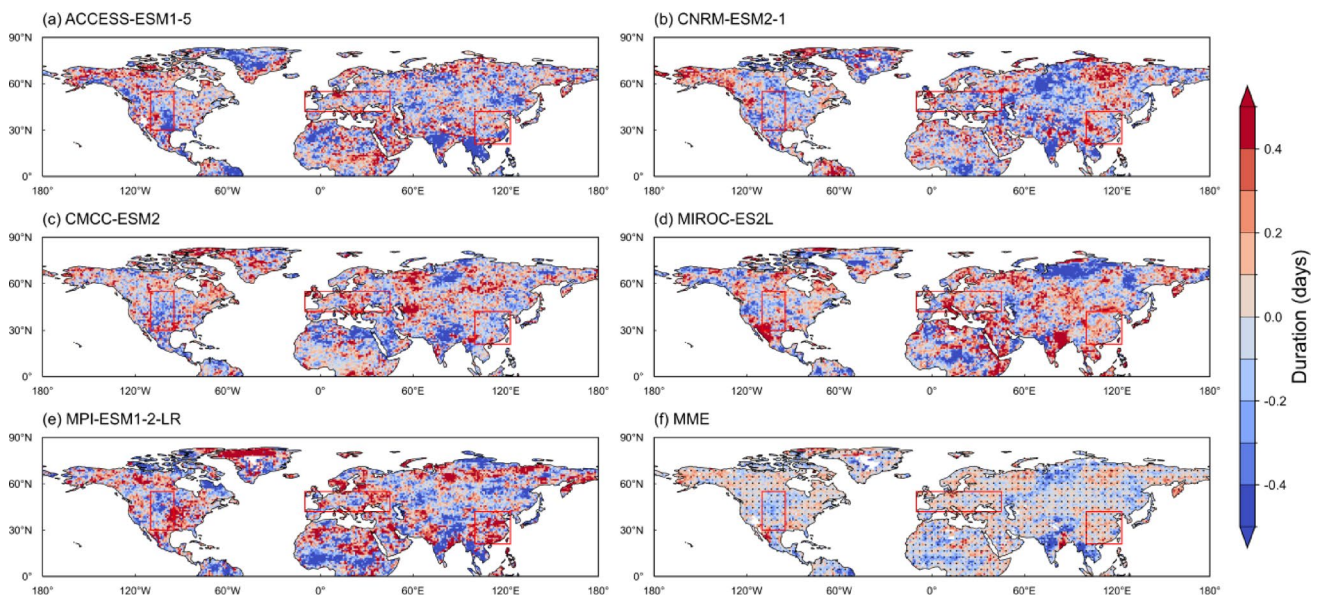


Fig. 7 The same as Fig. 3, but for LULCC-induced changes in the duration of CDHEs during 1980–2014

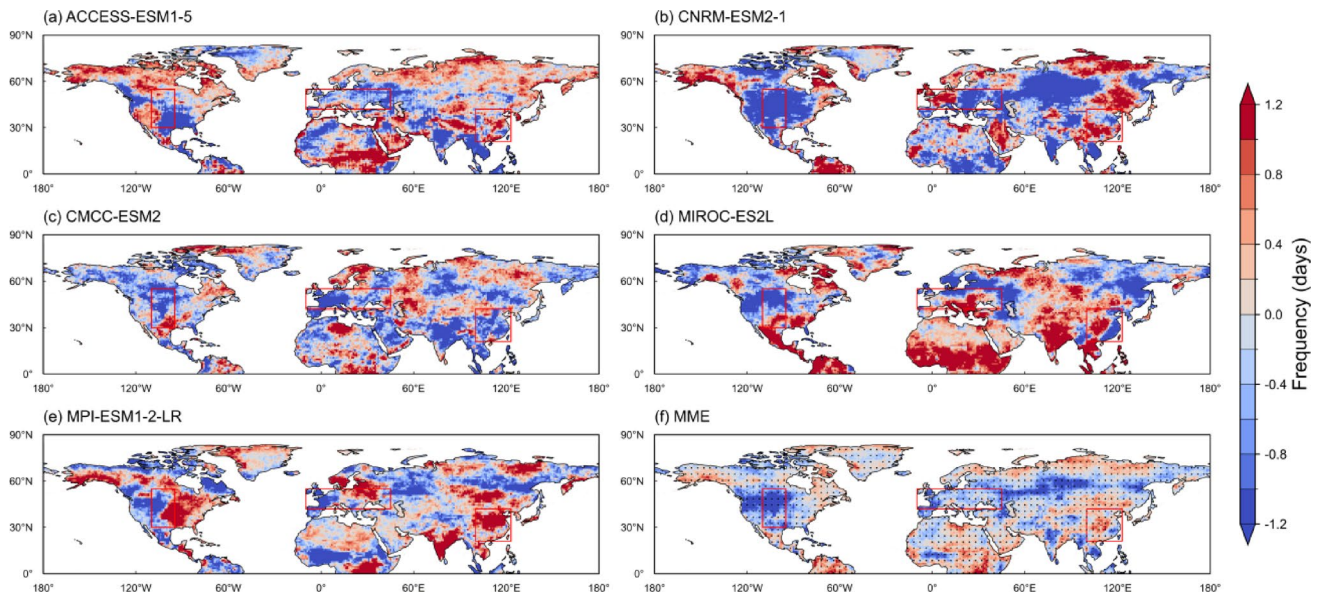


Fig. 8 The same as Fig. 3, but for LULCC-induced changes in the frequency of CDHEs during 1980–2014

west-east dipole pattern with decreases in the west but increases in the east (Fig. 5e). The MME shows a consistent decrease across NA, with a maximum reduction of more than 0.2 events per year (Fig. 5f). In the EU, two models (ACCESS-ESM1-5, CMCC-ESM2) show decreased CDHE occurrences in most areas (Fig. 5a and c). CNRM-ESM2-1 shows increased CDHE occurrences in the western and decreased occurrences in the east (Fig. 5b). MIROC-ES2L exhibits decreased occurrences in the north but increased occurrences in the south (Fig. 5d), and MPI-ESM1-2-LR shows a similar west-east dipole pattern (Fig. 5e). The MME shows general decreased occurrences across the EU,

with a maximum reduction of more than 0.2 events per year (Fig. 5f). In CN, three out of the five models (ACCESS-ESM1-5, CNRM-ESM2-1, MPI-ESM1-2-LR) show an increased occurrence in most areas (Fig. 5a–b and e). CMCC-ESM2 shows a general decrease in CDHE occurrences (Fig. 5c), and MIROC-ES2L shows increased occurrences in the west and decreased occurrences in the east (Fig. 5d). The MME shows increased occurrences over central and western CN and a localized decrease in parts of the east (Fig. 5f), with both increases and decreases exceeding 0.1 events per year.

For the effects of LULCC on the changes in CDHE intensity, all five models generally indicate a decrease across NA, though some regions show increases due to spatial heterogeneity (Figs. 6a–e). The MME shows widespread reduction, with a maximum decrease exceeding $0.3\text{ }^{\circ}\text{C}$ per year (Fig. 6f). In the EU, three models (ACCESS-ESM1-5, CNRM-ESM2-1, MIROC-ES2L) project decreased intensity (Fig. 6a–b and d). CMCC-ESM2 shows increases (Fig. 6c), and MPI-ESM1-2-LR reveals a west-east dipole (Fig. 6e). The MME confirms this spatial pattern, with both the maximum increase and decrease exceeding $0.2\text{ }^{\circ}\text{C}$ per year (Fig. 6f). In CN, three models (CNRM-ESM2-1, MIROC-ES2L, MPI-ESM1-2-LR) indicate increased intensity (Fig. 6b and d–e), while ACCESS-ESM1-5 and CMCC-ESM2 suggest reductions (Fig. 6a and c). The MME projects increased intensity across most regions (Fig. 6f), with a maximum increase over $0.2\text{ }^{\circ}\text{C}$ per year.

For the effects of LULCC on duration changes of CDHEs, all five models exhibit strong spatial heterogeneity over NA, but most regions show a decrease (Figs. 7a–e). The MME confirms this trend with a maximum reduction of more than 0.1 days per year (Fig. 7f). In the EU and CN, both the models and MME reveal spatially heterogeneous changes, but the MME indicates an increase in most regions of CN (Fig. 7f).

Regarding the LULCC effects on frequency changes of CDHEs, in NA, ACCESS-ESM1-5 shows increased frequency only in a small southwestern area, with decreases elsewhere (Fig. 8a). CNRM-ESM2-1 exhibits widespread reductions (Fig. 8b). CMCC-ESM2 and MIROC-ES2L show a north-south dipole (Figs. 8c–d), and MPI-ESM1-2-LR shows a west-east dipole (Fig. 8e). The MME shows a general decline, with a maximum decrease of over 1.2 days per year (Fig. 8f). In the EU, most models show spatially variable patterns, with ACCESS-ESM1-5 and CMCC-ESM2 indicating widespread decreases (Fig. 8a and c), while others show dipole structures. (Figure 8b and d–e). The MME reveals a general decrease with reductions exceeding 1.2 days per year (Fig. 8f). In CN, ACCESS-ESM1-5, CNRM-ESM2-1 and MPI-ESM1-2-LR show increased frequency (Fig. 8a–b and e), while CMCC-ESM2 shows decreased frequency (Fig. 8c). MIROC-ES2L shows a west-east dipole (Fig. 8d). The MME reveals a general increase with a maximum increase exceeding 0.6 days per year (Fig. 8f).

3.4 Annual variations of CDHEs characteristics driven by LULCC

In this section, we analyze the interannual variations of CDHE characteristics induced by LULCC across these three regions. For the annual variations of CDHE occurrences

(Figs. 9a–c), the LULCC-induced effect, represented as Historical minus Hist-noLu, reveals a negative trend in NA (-0.09 events/decade), indicating that LULCC has suppressed the increasing trend in CDHE occurrences. In contrast, it slightly enhances the rising trends in the EU ($+0.04$ events/decade) and CN ($+0.03$ events/decade). Regarding the temporal variations of CDHE intensity (Figs. 9d–f), CDHE intensity trends are generally weak, in NA and EU, LULCC contributes a slight dampening effect ($-0.05\text{ }^{\circ}\text{C}/\text{decade}$ and $-0.18\text{ }^{\circ}\text{C}/\text{decade}$, respectively), while in CN, it exerts a slight intensifying effect ($+0.15\text{ }^{\circ}\text{C}/\text{decade}$). For the annual variations of average duration of CDHEs across different regions (Figs. 9g–i), LULCC induced changes suggest slight shortening trend in NA (-0.06 days/decade) and EU (-0.01 days/decade), contrasted with a minor lengthening trend in CN ($+0.03$ days/decade). For the annual variations of frequency of CDHEs across different regions, the LULCC-induced effect is a net reduction in CDHE frequency in NA (-0.45 days/decade), but importantly, an enhancement in EU ($+0.15$ days/decade) and CN ($+0.16$ days/decade). However, these trends were not statistically significant.

3.5 Possible mechanisms underlying the LULCC effects on climate and CDHEs

In this section, we investigate the possible mechanisms underlying the LULCC effects on CDHEs based on several surface variables, i.e., SH LH, NR, ET, SM, and LAI. This selection is grounded in the theoretical framework of Davin and De Noblet-Ducoudré (2010), who established a systematic distinction between radiative and non-radiative pathways through which LULCC influences surface temperature. Specifically, NR characterizes the radiative pathway, which is mediated by LULCC-induced changes in surface albedo (Boisier et al. 2012; Betts 2000), while SH and LH characterize the non-radiative pathway, reflecting changes in the partitioning of available surface energy (Pielke et al., 2002; Burakowski et al. 2018). ET and LAI are included as key determinants of LULCC impacts on precipitation and evapotranspiration efficiency, respectively (Luo et al. 2022), and SM serves as a core mediating variable in land-atmosphere coupling, regulating both surface temperature and precipitation (Seneviratne et al. 2018). In addition to these local land surface variables, we further examine LULCC-induced changes in Z500, 500 hPa wind fields, and IVT to assess the potential role of large-scale atmospheric circulation and non-local moisture transport in modulating CDHEs (Liu et al. 2023; Luo et al. 2024). Since CDHEs are simultaneously governed by temperature and precipitation variability, these variables collectively provide a physically

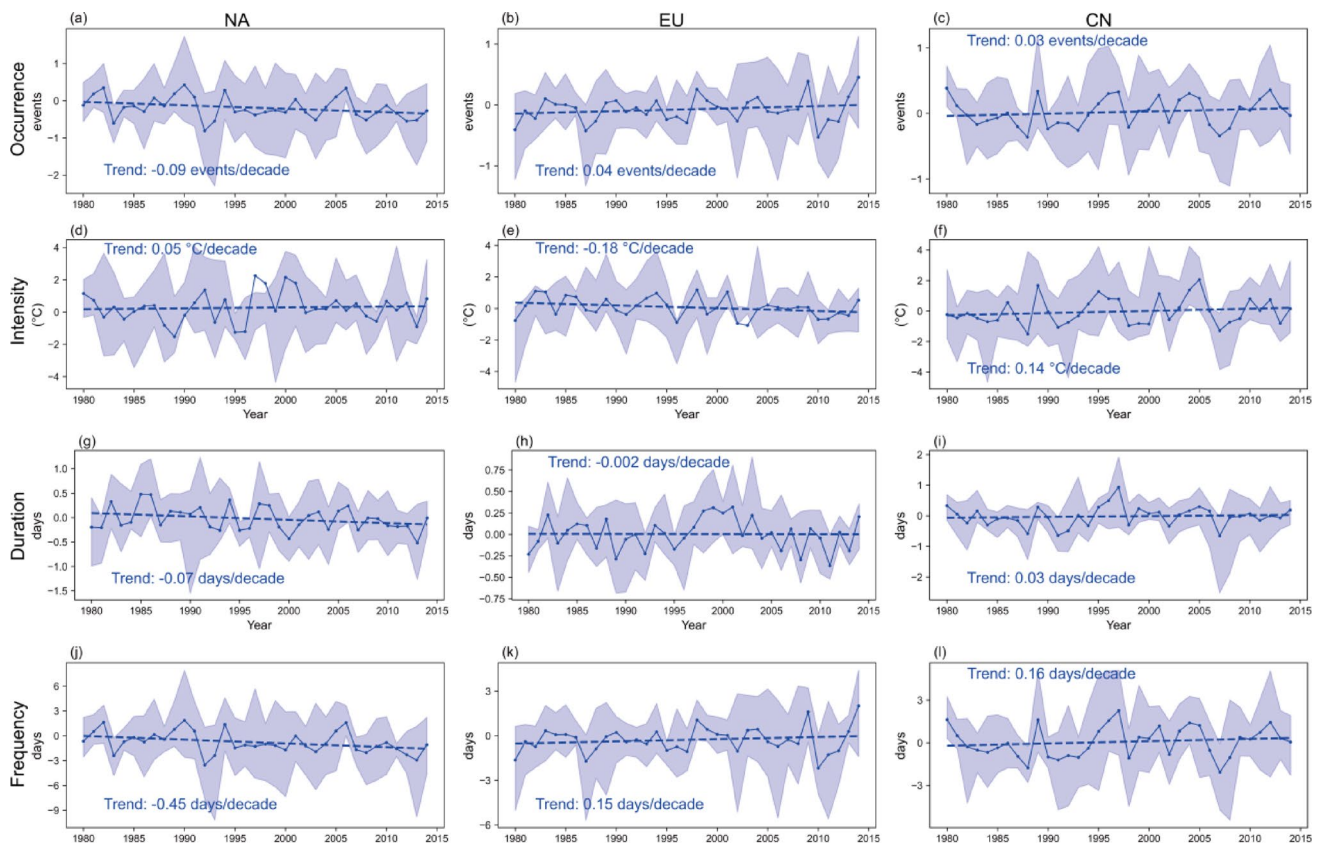


Fig. 9 Annual variations in CDHE characteristics induced by LULCC across three regions. The solid line represents the multi-model ensemble (MME) of Historical minus Hist-noLu, while the dashed line

shows the linear trends. The shaded areas represent the range from the minimum to the maximum values across all models

comprehensive framework for diagnosing the mechanisms through which LULCC modulates CDHE characteristics.

Figure 10 illustrates the spatial patterns of LULCC induced changes in summer mean SH, LH, ET, NR, SM and LAI based on the MME results. In NA, LULCC leads to a decrease in SH and an increase in LH, (Figs. 10a–b), which collectively contribute to a decrease in air temperature (Fig. 3f), despite a slight increase in NR (Fig. 10c). The elevated ET (Fig. 10d) further support increased Pr (Fig. 4f). In EU, LULCC leads to a decrease in SH (Fig. 10a), an increase in LH (Fig. 10b), and a reduction in NR (Fig. 10c), jointly leading to a decline in Tmax (Fig. 3f). The increases and ET (Fig. 10d) contribute to enhanced Pr (Fig. 4f). Meanwhile, we observed a significant increase in SM (Fig. 10e) and LAI (Fig. 10f) in NA and EU, which further promoted an increase in ET and a decrease in Tmax. Conversely, In CN, LULCC triggers an increase in SH (Fig. 10a) and a decrease in LH (Fig. 10b), which favors higher air temperatures despite a decline in NR (Fig. 10c). Concurrent decreases in ET are also associated with reduced Pr (Fig. 4f). A slight decrease in SM (Fig. 10e) and LAI (Fig. 10f) in CN also contributed to a reduction in ET and a rise in Tmax.

We further try to quantify whether radiative processes or non-radiative processes dominate the changes in Tmax and Pr induced by LULCC. Figure 11 demonstrates the regional mean SH, LH, NR, and ET changes in summer months induced by LULCC between 1980 and 2014 relative to 1850. It is indicated that LULCC leads to a decrease in SH ($-2.17 \text{ W} \cdot \text{m}^{-2}$ and $-0.34 \text{ W} \cdot \text{m}^{-2}$, respectively) and an increase in LH ($+2.83 \text{ W} \cdot \text{m}^{-2}$ and $+0.28 \text{ W} \cdot \text{m}^{-2}$, respectively) in both NA and EU. Despite a slight increase in NR in NA ($+0.53 \text{ W} \cdot \text{m}^{-2}$) and a small decrease in EU ($-0.05 \text{ W} \cdot \text{m}^{-2}$), non-radiative processes played the dominant role in modulating the thermal response. The reduction in SH combined with enhanced LH contributed to a net cooling effect, manifested as a decrease in Tmax in both regions as seen in Fig. 3. In contrast, LULCC in CN resulted in an increase in SH ($+0.26 \text{ W} \cdot \text{m}^{-2}$) and a decrease in LH ($+0.42 \text{ W} \cdot \text{m}^{-2}$). Although net radiation is also decreased ($-0.33 \text{ W} \cdot \text{m}^{-2}$), the non-radiative pathway again dominated, resulting in a rise in Tmax (Fig. 3f). In a word, these findings underscore the central role of non-radiative processes in controlling LULCC induced temperature changes across all the three regions. Moreover, it is found that the LULCC induced increased Pr in the NA and EU coincide with the increased

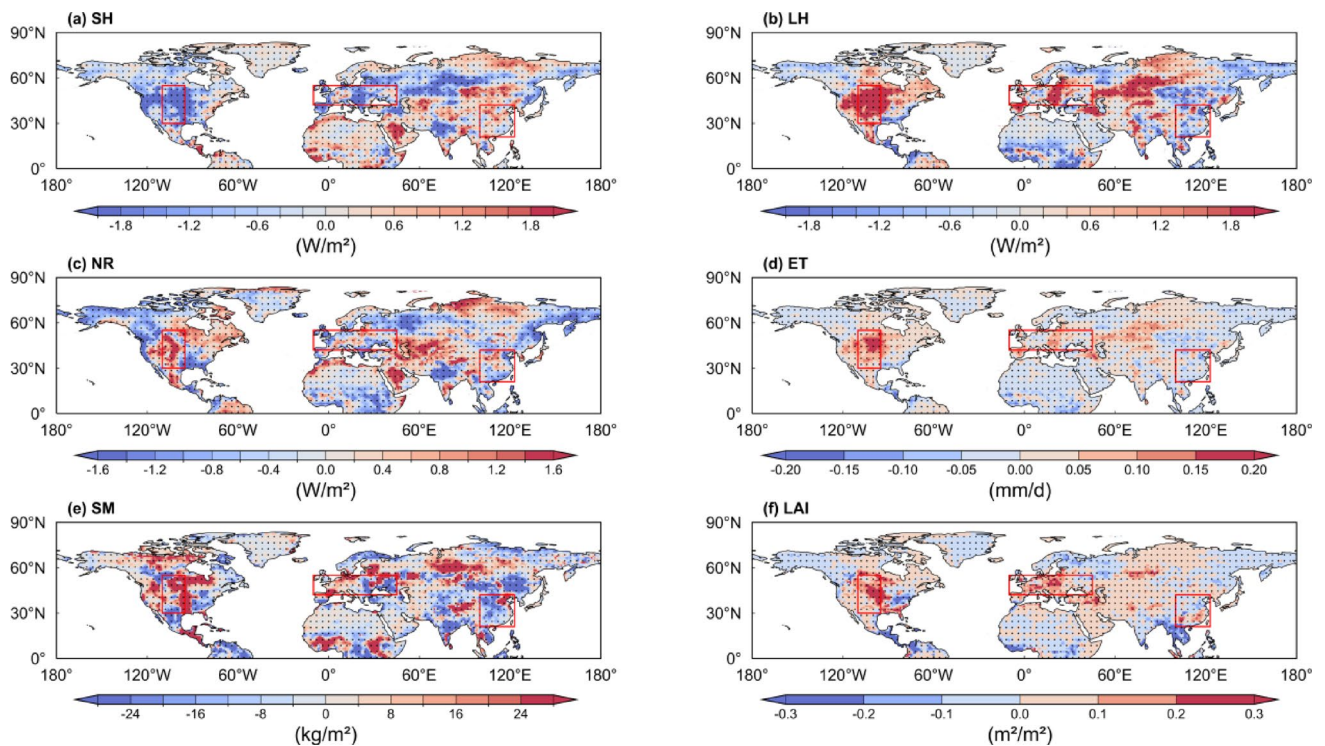


Fig. 10 Spatial patterns of LULCC-induced changes in summer mean (1980–2014) for **a** sensible heat flux (SH), **b** latent heat flux (LH), **c** net radiation (NR), **d** evapotranspiration (ET), **e** soil moisture (SM) and leaf area index (LAI). Red boxes denote the three study regions:

North America (NA), Europe (EU), and China (CN). Stippling indicates regions where at least three out of five models agree on the sign of the change

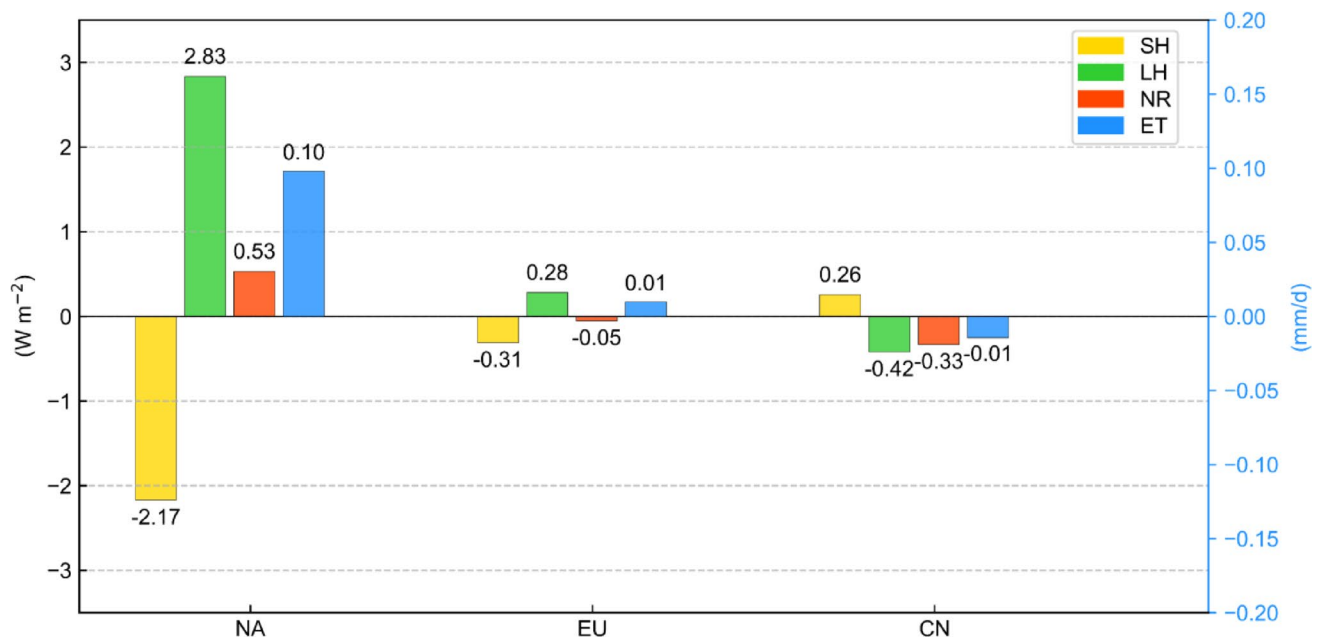


Fig. 11 Regional average changes in physical variables during summer of 1980–2014 caused by LULCC over three regions (NA, EU, and CN). Sensible heat flux (SH), latent heat flux (LH), and net radiation

(NR) are plotted using the left y-axis ($W m^{-2}$); evapotranspiration (ET) uses the right y-axis ($mm d^{-1}$). All results are based on the multi-model ensemble (MME) mean

ET, and LH. In CN, in contrast, decreased Pr is consistent with reductions in ET, and LH. These results suggest that LULCC driven Pr changes are closely linked to land surface processes, governing local moisture cycling and surface energy, which in turn modulate Pr patterns. Therefore, the LULCC induced decreases in Tmax and increases in Pr over NA and EU have contributed to reduced CDHE occurrences, whereas the increased Tmax and decreased Pr over CN have led to more frequent CDHEs.

The differences between LULCC induced changes in climate and CDHEs across NA, EU and CN are driven by region-specific land conversion patterns. In NA, LULCC mainly involves the transformation of primary grasslands into croplands (Waisanen et al. 2002; Sohl et al. 2012), which leads to an increase in higher LH, and lower SH, and a cooling effect. Additionally, elevated ET from irrigated croplands has enhanced Pr over NA (Mahmood et al. 2002). In the EU, non-forest areas have been converted predominantly into croplands and forests (Ramankutty et al. 2006), resulting in similar effects, i.e., increased LH, reduced SH, and a cooling effect. Both croplands and forests contribute to increased ET, further promoting Pr. In contrast, in CN, the conversion of forest to cropland has weakened soil water retention due to reduced root systems (Yin et al. 2015), causing a decline in LH and an increase SH, and a warming effect, as well as the decreased ET, further reducing Pr.

In addition to local land–atmosphere coupling processes, large-scale atmospheric circulation anomalies induced by LULCC may also play an important role in shaping CDHEs through non-local pathway. As shown in Fig. 12, LULCC induces distinct circulation anomalies over the three key regions during summer. Over CN, LULCC drives a significant positive Z500 anomaly (Fig. 12a), accompanied by anomalous anticyclonic circulation. This upper-level high-pressure anomaly suppresses vertical motion and reduces cloud cover, thereby promoting surface warming and inhibiting precipitation. Consistently, the IVT divergence analysis (Fig. 12b) reveals anomalous moisture divergence over CN, indicating a reduction in moisture convergence that further suppresses precipitation and amplifies CDHE risk. In contrast, over EU, LULCC is associated with negative Z500 anomalies, corresponding to anomalous cyclonic circulation that favors increased moisture convergence, as evidenced by the negative IVT divergence anomaly over this region, thereby contributing to reduced CDHEs. Over NA, the region is located on the eastern flank of negative Z500 anomalies, where anomalous southerly facilitates moisture transport into the region, consistent with the enhanced moisture convergence and increased precipitation identified in Sect. 3.2. These results suggest that the LULCC-induced CDHE responses are jointly shaped by local land surface feedbacks and non-local atmospheric circulation

adjustments. Their interplay modulates regional moisture transport and energy balance, ultimately determining CDHE variability, consistent with previous coupled model studies (Liu et al. 2023; Luo et al. 2024).

4 Conclusions and discussion

This study uses CMIP6 LUMIP model simulations to investigate the impacts of LULCC on CDHEs during summer in the Northern Hemisphere. Given the pronounced inter-model differences in LULCC-induced climate responses, we analyze both individual model and the MME results. The main conclusions are as follows:

- (1) The MME reveals that LULCC exerts a cooling effect on summer Tmax over NA and EU, while inducing a warming effect over most of CN. Correspondingly, LULCC generally enhances summer Pr over NA and EU but suppresses it over most of CN. These spatially contrasting responses in Tmax and Pr translate into distinct regional differences in CDHE characteristics.
- (2) Consistent with the changes in Tmax and Pr, LULCC reduces the occurrence and frequency of CDHEs in NA and EU, while intensifying them in CN. The spatial responses of CDHE intensity and duration, however, exhibit considerable heterogeneity across all three regions.
- (3) The LULCC-induced CDHE responses are shaped by the combined effects of local biogeophysical feedbacks and non-local atmospheric circulation adjustments. Locally, in NA and EU, LULCC enhances LH and reduces SH, with non-radiative processes dominating the temperature response and producing a cooling effect despite slight changes in NR. Increased LAI, ET, and SM further reinforce the cooling and moistening, contributing to enhanced Pr. In CN, LULCC increases SH and reduces LH, with non-radiative feedbacks driving a rise in Tmax despite a decrease in NR. Concurrent decreases in LAI, ET, and SM further suppress Pr and amplify warming. At the large scale, LULCC drives a positive Z500 anomaly and anomalous anticyclonic circulation over CN, suppressing moisture convergence and vertical motion, thereby further amplifying CDHE risk. In contrast, negative Z500 anomalies and associated cyclonic circulation over NA and EU enhance moisture convergence, reinforcing precipitation increases and suppressing CDHE development.

LULCC represents an important anthropogenic forcing in the climate system and substantially modulate regional climate variability and change over the past century. This

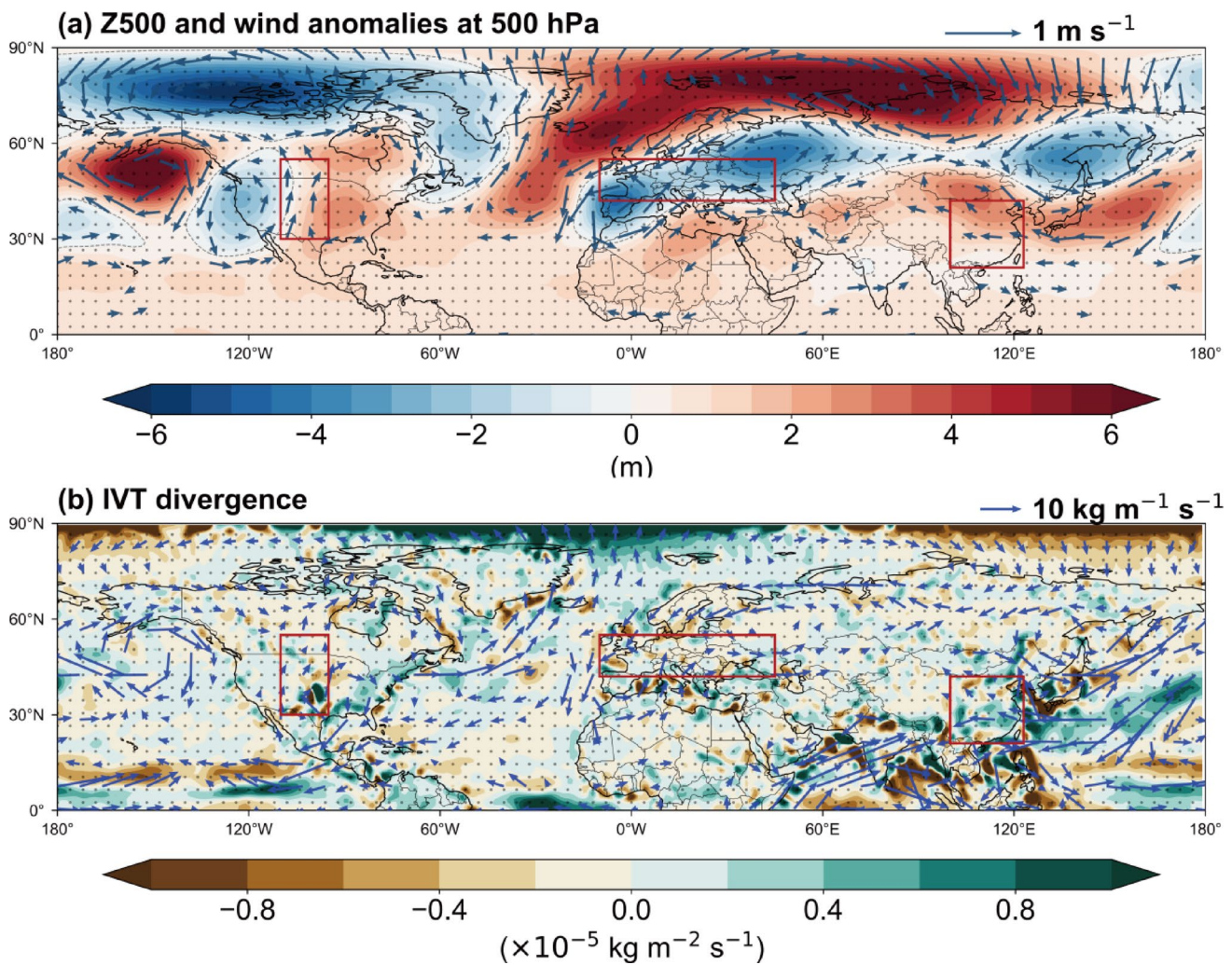


Fig. 12 Spatial distribution of LULCC-induced changes in summer mean (1980–2014) for **a** 500 hPa geopotential height (Z500, m) and 500 hPa wind field (vectors, m s⁻¹), and **b** vertically integrated moisture flux divergence (IVT divergence, ×10⁻⁵ kg m⁻² s⁻¹) and vertically integrated moisture flux (vectors, kg m⁻¹ s⁻¹), based on the multi-model

ensemble mean (Historical minus Hist-noLu). Red boxes denote the three study regions: North America (NA), Europe (EU), and China (CN). Stippling indicates regions where at least three out of five models agree on the sign of the change

study contributes to advancing the understanding of the LULCC biogeophysical effects on not only the individual climate variables but also the compound extremes. However, given the notable uncertainties of LULCC impacts on climate and CDHEs across CMIP6 multi-models, more efforts are needed to advance the climate model representations of land-atmosphere coupling. Moreover, we only consider the biogeophysical effects of LULCC, whereas the biogeochemical feedbacks such as carbon-climate interactions and aerosol emissions may exert substantial influence on regional and global climate (Liu et al. 2022; Hibbard et al. 2017), and thus the biogeochemical effects of LULCC on CDHEs warrant further investigation.

Although the models employed in this study are capable of reproducing present-day climatological features, their ability to accurately represent the biogeophysical effects of

LULCC remains uncertain. Previous studies have revealed systematic deficiencies in simulating surface energy balance responses and biogeophysical feedbacks associated with LULCC (e.g., Ge et al. 2021; Luo et al. 2023). Due to the limited availability of long-term, high-resolution observational datasets, direct evaluation of the modeled LULCC-induced biogeophysical effects was not feasible in this study. Consequently, our findings should be interpreted with caution, as potential model biases in surface albedo, evapotranspiration, or land-atmosphere coupling strength may influence the simulated responses. Future work incorporating multi-model ensembles and observational constraints would be beneficial to reduce these uncertainties and enhance confidence in the results.

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1007/s00382-0>

26-08229-6.

Acknowledgements This study was supported by the National Natural Science Foundation of China (Grant 42521006 and 42475032), and the Natural Science Foundation of Jiangsu Province (Grant BK20241902).

Author contributions P. Wang performed the analyses and wrote the initial draft. Y. Zheng edited the initial draft. M. Li improved the visualization of the figure. Y. Song improved the visualization of the figure. Y. Yang reviewed and edited the initial draft. All the authors discussed the results and contributed to the final manuscript.

Data availability All datasets used in this study can be obtained from public sources. The outputs of CMIP6 multi-model simulations are available at <https://aims2.llnl.gov/search/cmip6/>. The LUH2 dataset is accessible from <https://luh.umd.edu/index.shtml>.

Declarations

Competing interests The authors declare that they have no competing interest.

References

- Alessi MJ, Herrera DA, Evans CP et al (2022) Soil moisture conditions determine land-atmosphere coupling and drought risk in the northeastern United States. *J Geophys Res: Atmos* 127(6): e2021JD034740
- Betts RA (2000) Offset of the potential carbon sink from boreal forestation by decreases in surface albedo. *Nature* 408(6809):187–190
- Boisier JP, De Noblet-Ducoudré N, Pitman AJ et al (2012) Attributing the impacts of land-cover changes in temperate regions on surface temperature and heat fluxes to specific causes: results from the first LUCID set of simulations. *J Geophys Res: Atmos* 117:D12
- Bright RM (2015) Metrics for biogeophysical climate forcings from land use and land cover changes and their inclusion in life cycle assessment: a critical review. *Environ Sci Technol* 49(6):3291–3303
- Brovkin V, Boysen L, Arora VK et al (2013) Effect of anthropogenic land-use and land-cover changes on climate and land carbon storage in CMIP5 projections for the twenty-first century. *J Clim* 26(18):6859–6881
- Burakowski E, Tawfik A, Ouimette A et al (2018) The role of surface roughness, albedo, and Bowen ratio on ecosystem energy balance in the Eastern United States. *Agric For Meteorol* 249:367–376
- Campbell S, Remenyi TA, White CJ et al (2018) Heatwave and health impact research: a global review. *Health Place* 53:210–218
- Cheng L, Hoerling M, Liu Z et al (2019) Physical understanding of human-induced changes in US hot droughts using equilibrium climate simulations. *J Clim* 32(14):4431–4443
- Cheng F, Chang M, Zuo Z et al (2025) Profile of climate extremes vulnerability in China during 1991–2022. *Sci Bull* 70(16):2547–2550
- Davin EL, De Noblet-Ducoudré N (2010) Climatic impact of global-scale deforestation: radiative versus nonradiative processes. *J Clim* 23(1):97–112
- De Noblet-Ducoudré N, Boisier JP, Pitman A et al (2012) Determining robust impacts of land-use-induced land cover changes on surface climate over North America and Eurasia: results from the first set of LUCID experiments. *J Clim* 25(9):3261–3281
- Feng Y, Wang H, Sun F et al (2023) Dependence of compound hot and dry extremes on individual ones across China during 1961–2014. *Atmos Res* 283:106553
- Findell KL, Shevliakova E, Milly PCD et al (2007) Modeled impact of anthropogenic land cover change on climate. *J Clim* 20(14):3621–3634
- Findell KL, Berg A, Gentile P et al (2017) The impact of anthropogenic land use and land cover change on regional climate extremes. *Nat Commun* 8(1):989
- Ge J, Qiu B, Chu B et al (2021) Evaluation of coupled regional climate models in representing the local biophysical effects of afforestation over continental China. *J Clim* 34(24):9879–9898
- Ge J, Liu Q, Zan B et al (2022) Deforestation intensifies daily temperature variability in the northern extratropics. *Nat Commun* 13(1):5955
- Hajima T et al (2020) Development of the MIROC-ES2L earth system model and the evaluation of biogeochemical processes and feedbacks. *Geosci Model Dev* 13:2197–2244
- Hibbard K, Hoffman F, Huntzinger DN et al (2017) Changes in land cover and terrestrial biogeochemistry. In: Wuebbles DJ et al (eds) *Climate Science Special Report: A Sustained Assessment Activity of the U.S. Global Change Research Program*. the U.S. Department of Commerce, Washington, DC, pp 405–442
- Hong T, Wu J, Kang X et al (2022) Impacts of different land use scenarios on future global and regional climate extremes. *Atmosphere* 13(6):995
- Hua WJ, Chen HS (2013) Impacts of regional-scale land use/land cover change on diurnal temperature range. *Adv Clim change Res* 4(3):166–172
- Hurt GC, Chini L et al (2020) Harmonization of global land use change and management for the period 850–2100 (LUH2) for CMIP6. *Geosci Model Dev* 13:5425–5464
- Lawrence DM et al (2016) The Land Use Model Intercomparison Project (LUMIP) contribution to CMIP6: rationale and experimental design. *Geosci Model Dev* 9(9):2973–2998
- Lee X, Goulden ML, Hollinger DY et al (2011) Observed increase in local cooling effect of deforestation at higher latitudes. *Nature* 479(7373):384–387
- Leonard M, Westra S, Phatak A et al (2014) A compound event framework for understanding extreme impacts. *Wiley Interdisciplinary Rev: Clim Change* 5(1):113–128
- Liu S, Wang Y, Zhang GJ et al (2022) Contrasting influences of biogeophysical and biogeochemical impacts of historical land use on global economic inequality. *Nat Commun* 13(1):2479
- Liu SY, Hua WJ, Zhou LM et al (2023) Local and non-local biophysical impacts of deforestation on global temperature during boreal summer: CMIP6-LUMIP multimodel analysis. *J Geophys Research: Atmos* 128:e2022JD038229.
- Luo X, Ge J, Guo W et al (2022) The biophysical impacts of deforestation on precipitation: results from the CMIP6 model intercomparison. *J Clim* 35(11):3293–3311
- Luo X, Ge J, Guo W et al (2023) An evaluation of CMIP6 models in representing the biophysical effects of deforestation with satellite-based observations. *J Geophys Res: Atmos* 128(12): e2022JD038198
- Luo X, Ge J, Cao Y et al (2024) Local and nonlocal biophysical effects of historical land use and land cover changes in CMIP6 models and the intermodel uncertainty. *Earth's Future* 12(6): e2023EF004220
- Mahmood R, Hubbard KG (2002) Anthropogenic land-use change in the North American tall grass-short grass transition and modification of near-surface hydrologic cycle. *Climate Res* 21(1):83–90
- Mahmood R, Pielke Sr RA, Hubbard KG et al (2014) Land cover changes and their biogeophysical effects on climate. *Int J Climatol* 34(4):929–953
- Miralles DG, Van Den Berg MJ, Teuling AJ et al (2012) Soil moisture-temperature coupling: a multiscale observational analysis. *Geophys Res Lett* 39(21). <https://doi.org/10.1029/2012GL053703>

- Miralles DG, Vilà-Guerau de Arellano J, McVicar TR et al (2025) Vegetation-climate feedbacks across scales. *Annals New York Academy Sci* 1544:27–41
- Perkins-Kirkpatrick SE, Lewis SC (2020) Increasing trends in regional heatwaves. *Nat Commun* 11(1):3357
- Pielke RA, Avissar RI, Raupach M et al (1998) Interactions between the atmosphere and terrestrial ecosystems: influence on weather and climate. *Glob Change Biol* 4(5):461–475
- Pielke Sr RA, Marland G, Betts RA et al (2002) The influence of land-use change and landscape dynamics on the climate system: relevance to climate-change policy beyond the radiative effect of greenhouse gases. *Ser A: Math Phys Eng Sci Philosoph Transact Royal Soc London* 360(1797):1705–1719
- Pielke Sr RA, Pitman A, Niyogi D et al (2011) Land use/land cover changes and climate: modeling analysis and observational evidence. *Wiley Interdisciplinary Rev: Clim Change* 2(6):828–850
- Pitman AJ, de Noblet-Ducoudré N, Cruz FT et al (2009) Uncertainties in climate responses to past land cover change: first results from the LUCID intercomparison study. *Geophys Res Lett* 36(14). <https://doi.org/10.1029/2009GL039076>
- Pitman AJ, de Noblet-Ducoudré N, Avila FB et al (2012) Effects of land cover change on temperature and rainfall extremes in multi-model ensemble simulations. *Earth Sys Dyn* 3(2):213–231
- Pongratz J, Reick CH, Raddatz T et al (2010) Biogeophysical versus biogeochemical climate response to historical anthropogenic land cover change. *Geophys Res Lett* 37(8). <https://doi.org/10.1029/2010GL043010>
- Pongratz J, Schwingshackl C, Bultan S et al (2021) Land use effects on climate: current state, recent progress, and emerging topics. *Curr Clim Change Rep* 7(4):99–120
- Ramankutty N et al (2006) Global Land-Cover Change: Recent Progress, Remaining Challenges. In: Lambin EF, Geist H (eds) *Land-Use and Land-Cover Change*. Springer, Berlin, Heidelberg, pp 9–39
- Seneviratne SI, Corti T, Davin EL, Hirschi M, Jaeger EB, Lehner I, Teuling AJ (2010) Investigating soil moisture–climate interactions in a changing climate: a review. *Earth Sci Rev* 99(3–4):125–161
- Seneviratne SI et al (2018) Climate extremes, land–climate feedbacks and land-use forcing at 1.5°C. *Philosoph Transact Royal Soc A: Mathemat Physic Eng Sci* 376(2119):20160450. <https://doi.org/10.1098/rsta.2016.0450>
- Sohl TL, Sleeter BM, Sayler KL et al (2012) Spatially explicit land-use and land-cover scenarios for the great plains of the United States. *Agricult Ecosyst Environ* 153:1–15
- Tang Z, Yang T, Lin X et al (2022) Future changes in the risk of compound hot and dry events over China estimated with two large ensembles. *PLoS ONE* 17(3):e0264980
- Tang T, Ge J, Shi H et al (2025) Divergent response of aridity index to historical land use and land cover change. *npj Clim Atmos Sci* 8(1):88
- Tavakol A, Rahmani V, Harrington J Jr (2020) Probability of compound climate extremes in a changing climate: a copula-based study of hot, dry, and windy events in the central United States. *Environ Res Lett* 15(10):104058
- Waisanen PJ, Norman B, Bliss (2002) Changes in population and agricultural land in conterminous United States counties, 1790–1997. *Glob Biogeochem Cycles* 16(4):84–81
- Wang P, Tang J, Sun X et al (2017) Heat waves in China: definitions, leading patterns, and connections to large-scale atmospheric circulation and SSTs. *J Geophys Research: Atmos* 122(20):10679–10699
- Wang AH, Miao Y, Shi XL (2021) Short commentary on the land-use model intercomparison project (LUMIP). *Adv Clim Change Res* 17(3):367–373
- Yang Y, Maraun D, Ossó A et al (2023) Increased spatial extent and likelihood of compound long-duration dry and hot events in China, 1961–2014. *Nat Hazards Earth Syst Sci Discuss* 23(2):1–26
- Ye F, Wang P, Yang Y et al (2025) Anthropogenic forcing dominates changes in compound long-duration dry and heat extremes in China. *Clim Change* 178:3
- Yin J, Zheng Y, Zhan X et al (2015) An assessment of impacts of land-cover changes on root-zone soil moisture. *Int J Remote Sens* 36(24):6116–6134
- Zeng J, Zhang S, Zhou S et al (2024) Comparison of the risks and drivers of compound hot-dry and hot-wet extremes in a warming world. *Environ Res Lett* 19(11):114026
- Zhang M, Gao Y, Wang A et al (2024a) Land use change impacts on climate extremes over the historical period. *Clim Dyn* 62(9):8993–9011
- Zhang M, Gao Y, Zhang L et al (2024b) Impacts of anthropogenic land use and land cover change on climate extremes based on CMIP6-LUMIP experiments: part II. Future period. *Clim Dyn* 62(5):3669–3688
- Zhou J, Jiang T, Wang Y et al (2020) Spatiotemporal variations of aridity index over the Belt and Road region under the 1.5 C and 2.0 C warming scenarios. *J Geog Sci* 30:37–52

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.