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NOTES AND CORRESPONDENCE

Numerical Study of the Impacts of Land Use/Cover Changes Between 1700 and 1850 on the Seasonal Hydroclimate in Monsoon Asia

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Abstract

This study investigated the impacts of historical land use/cover changes (LUCC), from forest to cultivated land, on the seasonal cycle of the hydroclimate over the Indian subcontinent and southern China. The mechanism of these impacts was studied by conducting numerical experiments using an atmospheric general circulation model MIROC3.2 coupled with the land surface scheme MATSIRO and historical global land use/cover changes between 1700 and 1850. A previous study found a decrease in summer (JJA) precipitation over the Indian subcontinent and southern China induced by extended cultivation between 1700 and 1850. We further found that evapotranspiration in the Indian subcontinent notably decreased, particularly in the spring, while that in southern China discernibly decreased throughout the year. The difference in the changes in evapotranspiration in the spring over both regions could be explained by the amount of precipitation during the dry season. In the Indian subcontinent, the marked decrease in evapotranspiration in May due to LUCC caused the decrease in precipitation during the same season. However, in southern China, the decrease of precipitation from March to April was contributed rather by the decrease of water vapor flux convergence due to atmospheric circulation changes than by the decrease of evapotranspiration.

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1. Introduction

Vegetation plays an important role in the land-atmosphere interaction, by impacting the energy and water balances at the earth's surface. In the past, numerical experiments were conducted assuming virtual land use/cover changes (hereafter LUCC; e.g., total deforestation of tropical rainforests over a tropical region) to evaluate the potential impact of vegetation changes on the local or global climate (e.g., Henderson-Sellers et al. 1993; McGuffie et al. 1995; Mabuchi et al. 2005). The impact of anthropogenic LUCC on climate was recently examined using current and natural vegetation datasets (e.g., Chase et al. 2000; Fu 2003). These studies were analyzed for a specific season (i.e., JJA or DJF) or for a specific month (i.e., July or January). Voldoire and Royer (2004) evaluated the details of the impact of deforestation in Africa and the Amazon regions on their regional climates, using a general circulation model (GCM) with virtual deforestation. They found that deforestation in the southern Amazon and Africa caused the soil moisture to decrease throughout the year, and the soil evaporation to increase during the rainy season and decrease during the dry season. Findell et al. (2007) focused on the impact of anthropogenic LUCC on climate, using a GCM with current and natural vegetation datasets. They showed that soil moisture and latent heat flux in northern India decreased during the rainy season and was unchanged during the dry season.

Takata et al. (2009) investigated the impact of LUCC from forest to cultivated land between 1700 and 1850 on the Asian summer monsoon. They conducted GCM experiments using historical global land use/cover data reconstructed for the last 300 years, and they reported that extended cultivation from 1700 to 1850 significantly decreased precipitation during JJA over the Indian subcontinent (hereafter IND region) and southeastern China (hereafter SCH region). This result was consistent with the monsoon rainfall trend during this period derived from the Himalayan ice core (Duan et al. 2004). However, they discussed the impact on the Asian summer monsoon rainfall only during JJA.

The impacts of LUCC on the seasonal changes of precipitation and evapotranspiration over the Indian and China regions have been examined by Zhao et al. (2001) using GCM with natural and current vegetation datasets. They showed that precipitation decreased throughout the year over both regions. They also showed that latent heat flux decreased during MAM and increased during the other seasons over the Indian region, while it decreased throughout the year over the China region. However, they did not reveal the mechanism by which LUCC impacts precipitation and latent heat flux. Thus, in the Indian and China regions, the impact and its underlying mechanism of LUCC on the seasonal change of the local climate have not yet been examined in detail. Therefore, this study examined the changes in the seasonal cycle of the hydroclimate due to historical LUCC between 1700 and 1850 over the IND and SCH regions and their mechanisms, analyzing experiments data similar to Takata et al. (2009). These regions corresponded to the areas investigated by Takata et al. (2009), who found that precipitation in JJA was significantly decreased. Thus, this study is a follow-up of Takata et al. (2009) focused on the impact of historical LUCC on the seasonal cycle of the hydroclimate.

2. Experimental design

We conducted two equilibrium experiments in agreement with Takata et al. (2009), 1700VEG and 1850VEG. These experiments used an atmospheric general circulation model coupled with the land surface scheme MATSIRO (Takata et al. 2003). The model is the atmospheric portion of MIROC3.2 (K-1 Model Developers, 2004). The LAI (Leaf Area Index) datasets and the global distribution of vegetation type in 1700 and 1850 (derived from Hirabayashi et al. 2005) were used as boundary conditions in each equilibrium experiment (Fig. 1). The LUCC from 1700 to 1850 that resulted in cultivated land mainly occurred in India, central China, and Europe (Fig. 1). Other boundary conditions, such as the sea surface temperature and sea ice, were fixed at the observed monthly mean averaged from 1981 to 2000, and CO_2 was fixed at 345 ppm, which was its climatological value in the 1980s. Each experiment was conducted for 50 years. By analyzing the difference between 1700VEG and 1850VEG, we examined the monthly mean results for the latter 40-year mean to examine the effect of extended cultivation between 1700 and 1850 on seasonal changes in the hydroclimate.

3. Results

3.1 Common changes

In general, changes in the LAI due to LUCC affect the near surface wind speed and the heat/water

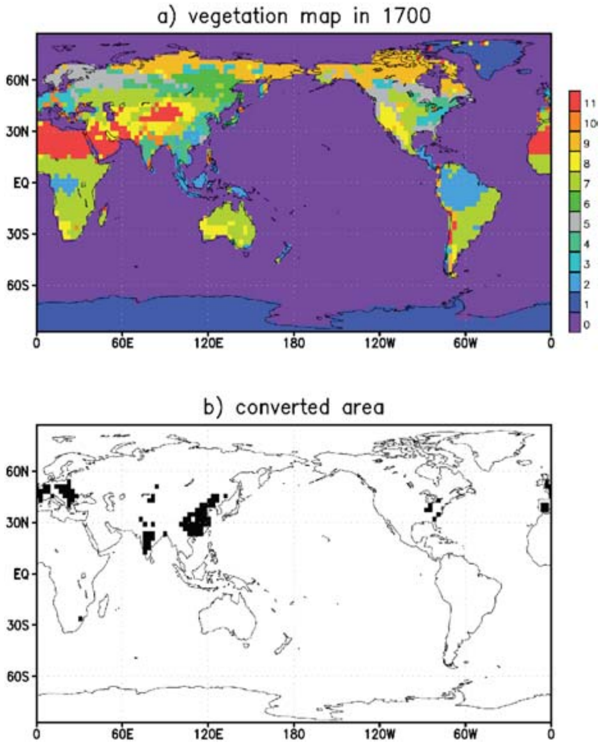

Fig. 1. The global distribution of a) the vegetation type in 1700, and b) the change in vegetation type between 1700 and 1850 (shades). The index numbers in a) are: 0—ocean; 1—ice sheet; 2—broadleaf evergreen forest; 3—broadleaf deciduous forest & woodland; 4—mixed coniferous & broadleaf deciduous forest & woodland; 5—coniferous forest & woodland; 6—high latitude deciduous forest & woodland; 7—wooded C4 grassland; 8—shrubs & bare ground; 9—tundra; 10—cropland; and 11—desert.

Table 1. Annual mean wind speed at 10 m [m s^{-1}; vabs10] and LAI [nondimensional].

	IND		SCH	
	1850VEG	1700VEG	1850VEG	1700VEG
vabs10	4.13	0.64	4.65	0.38
LAI	1.10	2.20	1.29	2.81

transport between the ground surface and the atmosphere. After extended cultivation from 1700 to 1850 in the IND (75–80 E, 20–22 N) and SCH (106–114 E, 22–28 N) regions, annual LAI values decreased by 50% and 54%, respectively, and the annual mean wind speed at 10 m increased by approximately 3.5 m s^{-1} and 4 m s^{-1}, respectively (Table 1).

3.2 Changes in the Indian Subcontinent

The upper bars of Fig. 2a indicate the seasonal variation of monthly precipitation in the IND region for each experiment. Rainy (over 2 mm day^{-1} precipitation) and dry (under 2 mm day^{-1} precipitation) seasons were reproduced in both experiments in this study. After extended cultivation, the monthly precipitation decreased in all months except for February and November. In particular, this decrease was greater than 1.2 mm day^{-1} in JJA and October, and greater than 0.8 mm day^{-1} in May. The decrease in JJA was similar to that discussed in detail by Takata et al. (2009).

We examined each component of evapotranspiration (hereafter EFLUX) in detail (Fig. 2a, lower bars). EFLUX is equal to the sum of transpiration (hereafter ETFLUX), interception evaporation (hereafter EIFLUX), soil evaporation (hereafter EBFLUX), and sublimation, although sublimation was negligible for the region discussed in this study. ETFLUX and EIFLUX decreased throughout the year after extended cultivation. In particular, the EIFLUX decrease was over 0.5 mm day^{-1} during JJA. It is noted that the decrease in EIFLUX was greatest during the rainy season, while the decrease in ETFLUX was greatest during the dry season. In contrast, EBFLUX decreased only during MAM and increased in the other months. As a result, the increase of EBFLUX partly compensated for the decrease of EIFLUX and ETFLUX in all months except for MAM. All evapotranspiration components decreased in 1850 compared to 1700 during MAM. Examining the sum of these components, the total EFLUX decreased in most of the months, although it slightly increased in October. In particular, it markedly decreased by at least 1 mm day^{-1} between the months of March and June; from March to June the difference between 1700 and 1850 was double the difference in other months. This large decrease in June was mostly due to the decrease of EIFLUX, although EBFLUX increased.

To explain the differences in the response of EBFLUX during MAM and the other months due to the historical LUCC, we examined the surface soil moisture (volumetric water content). Figure 3a shows the seasonal variation of the surface soil moisture in the IND region for each experiment as follows: 1) soil moisture accumulated by precipita-

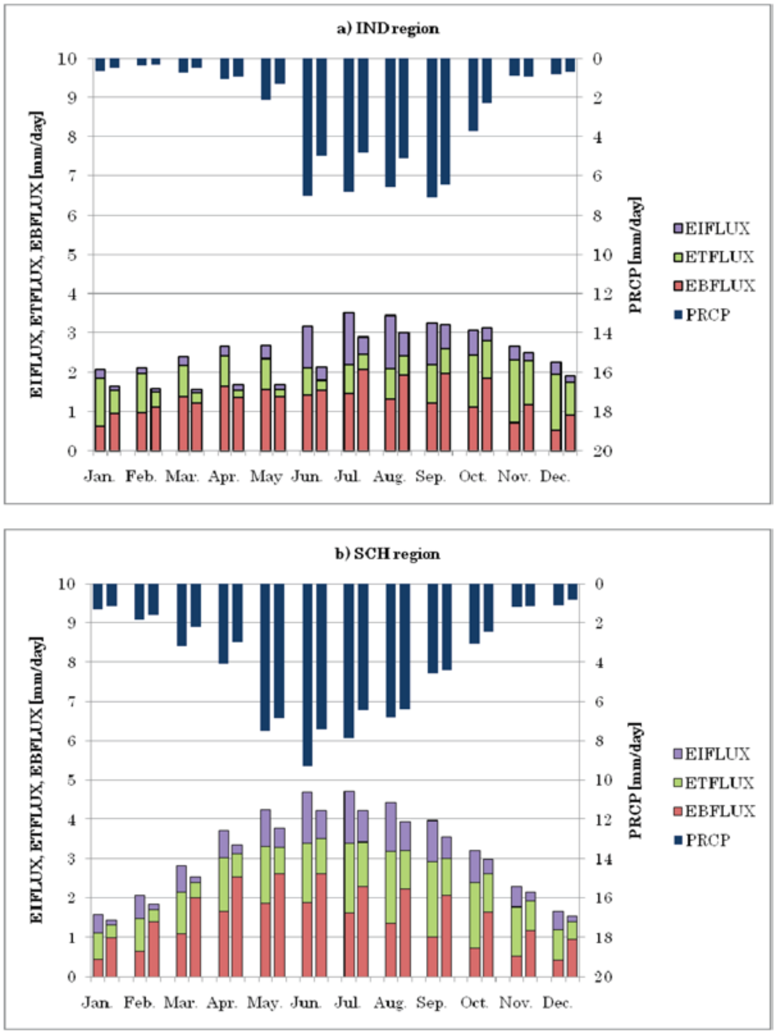

Fig. 2. The seasonal variation of evapotranspiration (below; mm day^{-1}) and precipitation (above; mm day^{-1}; PRCP). Evapotranspiration is represented by the sum of evaporation from the ground (EBFLUX), transpiration (ETFLUX), and interception evaporation (EIFLUX). The left (right) side vertical bar indicates 1700VEG (1850VEG) for each month. The left (right) side scale corresponds to evapotranspiration (precipitation). a) Indian Subcontinent (75–80°E, 20–22°N), b) South China (106–114°E, 22–28°N).

tion during JJAS (rainy season), 2) soil moisture gradually decreased by evapotranspiration during the dry season, 3) soil moisture became a minimum in May (immediately prior to rainy season). The amount of soil moisture throughout the year was decreased after the period of extended cultivation. This decrease was particularly noticeable during the dry season. During MAM, the soil moisture decrease was less than 0.15 m^3 m^{-3} due to extended cultivation.

In general, the increase in EBFLUX was induced by LUCC from forest to cultivated land, because decrease in the LAI induced exposure of the ground surface and a decrease in surface roughness, hence an increase in the near surface wind speed. However, the very low soil moisture during MAM induced a decrease in EBFLUX in those months.

During MAM, the largest ratio of decrease in the monthly precipitation occurred in May. To examine the relationship between this precipitation and the EFLUX decrease in May, we analyzed the total atmospheric water budget as:

$$\Delta PW = W + E - P \tag{1}$$

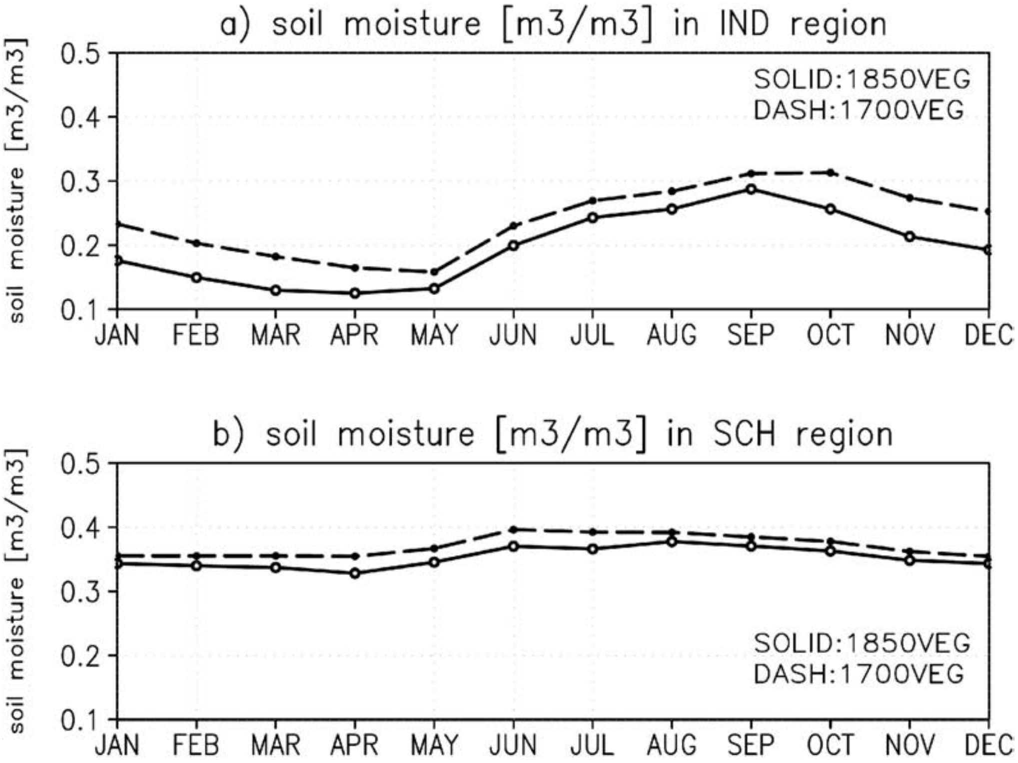

Fig. 3. The seasonal variation of surface soil moisture (0–5 cm) [m^{-3} m^{-3}]. a) Indian Subcontinent (75–80°E, 20–22°N), b) South China (106–114°E, 22–28°N).

Table 2. The total atmospheric water budget over the Indian subcontinent during May, and over South China during March and April. PRCP, EVAP, W.V.Flux, and ΔPW indicate the precipitation [mm], evapotranspiration [mm], water vapor flux convergence [mm], and the time rate of change of precipitable water [mm], respectively. DIFF indicates 1850VEG minus 1700VEG.

	IND in May			SCH during Mar–Apr.		
	1700VEG	1850VEG	DIFF	1700VEG	1850VEG	DIFF
PRCP	63.2	39.3	−23.9	219.3	155.9	−63.4
EVAP	80.5	50.4	−30.1	196.3	176.4	−19.9
W.V.Flux	−11.6	−8.56	3.04	39.7	−6.06	−45.76
ΔPW	−5.7	−2.54	3.16	−16.7	−14.44	2.26

where ΔPW is the rate of change of precipitable water, W is the water vapor flux convergence, E is the evapotranspiration, and P is the precipitation. An analysis of the total atmospheric water budget in May showed that the decrease in precipitation was mostly due to the decrease in EFLUX (Table 2). During this season, EFLUX strongly influences precipitation because monsoon activity is weak. Also, water vapor fluxes diverged over the IND region in both experiments. Therefore, the decrease in EFLUX induced by LUCC might dominantly affect the decrease in precipitation. In contrast, the reduced monthly precipitation in October was instead due to the decrease of water vapor flux convergence (not shown).

3.3 Changes in South China

Rainy and dry seasons were also recognizable in the SCH region (Fig. 2b, upper bars). The rainy season (monthly precipitation above 2 mm day^{-1})

occurred from March to October in both experiments. After the period of extended cultivation, there was reduced precipitation throughout the year, in addition to the decrease during JJA as mentioned by Takata et al. (2009). In particular, the precipitation decrease was over 0.8 mm day^{-1} from March to April and from June to July.

As before, we analyzed each component of EFLUX in the SCH region (Fig. 2b, lower bars). ETFLUX and EIFLUX decreased throughout the year, similarly to the IND region. However, EBFLUX increased throughout the year in the SCH region, which is in contrast to the marked decrease during MAM in the IND region. The net changes in EFLUX were to decrease throughout the year, from 0.1 to 0.5 mm day^{-1}.

There were little seasonal changes in the soil moisture, and soil was wet throughout the year in both experiments (Fig. 3b) due to the relatively large water supplies from precipitation. The minimum value in soil moisture after extended cultivation was over 0.3 $\text{m}^3\ \text{m}^{-3}$ and was much greater than that in the IND region, although soil moisture decreased throughout the year.

Although a marked decrease of EFLUX in MAM was not recognized, there was a decrease in monthly precipitation in March and April that exceeded 1 mm day^{-1} (Fig. 2b, upper bars). From the atmospheric water budget in March and April, it was found that the decrease in precipitation was due to the decrease in water vapor flux convergence instead of a decrease in EFLUX (Table 2). This might have been caused by a pre-monsoon condition in the SCH region. According to Matsumoto (1997), the summer rainy season begins in the inland region of Indochina and extends to South China in late April to early May; this is caused by pre-monsoon rainfall under the mid-latitude westerly wind regime. However, the summer monsoon season begins in south India in late May to early June, due to the enhancement of convective activity. Thus, precipitation over the SCH region in the spring is influenced by broad-scale atmospheric circulation. The historical LUCC remotely caused an anticyclone in March over the mid-China region, and in April over the Sea of Japan, Japan, and western Pacific regions (not shown). Therefore, the decrease in precipitation between March and April over the SCH region was induced by a decrease in water vapor flux convergence with the change of the broad-scale wind system over China. However, the mechanism underlying the impact of LUCC on broad-scale atmospheric circulation would be explained in further studies.

4. Discussion

This study investigated the impact of historical LUCC between 1700 and 1850 on the seasonal cycle of the hydroclimate over the IND and SCH regions, in addition to its underlying mechanism. We found a reduction in precipitation and evapotranspiration almost throughout the year in these two regions. In particular, EFLUX notably decreased during MAM in the IND region, but not in the SCH region. This marked decrease in the IND region was due to the decrease in EBFLUX.

The decrease of EBFLUX during MAM in the IND region is explained by the small amount of rainfall during the dry season, as follows. LUCC causes EBFLUX to increase from June to February, which led to a decrease in soil moisture during that same period. Moreover, there was little water supply to the ground (i.e., rainfall amount) during the dry season. Then, as the soil moisture during MAM was very low, the effect of soil moisture stress on EBFLUX overcame the effect of the LAI decrease, which usually acts to increase EBFLUX. Consequently, during MAM, the decrease in EBFLUX was induced by the very low amount of soil moisture.

However, a marked decrease of EFLUX during MAM did not appear in the SCH region. That was because the soil remained wet after extended cultivation due to the relatively large amount of rainfall during the dry season, compared with the amount of rainfall in the IND region.

The difference in the rainfall amounts during the dry season between the two regions may be caused by the differences in the located climate zone and the onset date. The IND and SCH regions are located in the Indian summer monsoon (ISM) and the East Asian summer monsoon (EASM), respectively. The ISM is a tropical monsoon, while the EASM is a subtropical monsoon (Wang and Lin Ho 2002). Moreover, the monsoon onset date over the SCH region is earlier than that over the IND region, as mentioned in Section 3.3. Consequently, there is less rainfall during the dry season in the IND region than there is in the SCH region, leading to an apparent decrease in soil moisture and EFLUX during MAM caused by LUCC in the IND region.

The mechanism underlying the impact of LUCC on EFLUX during the dry season agreed with that reported by Voldire and Royer (2004). They showed that, in the south Amazon and Africa regions, the Soil Wetness Index (SWI) during the dry season was close to zero after deforestation, which limited the soil evaporation increase. However, an increase in soil evaporation during the wet season compensated for the decrease in evapotranspiration. Thus, their result is consistent with ours.

Lee et al. (2009) showed that the increase of the Normalized Difference Vegetation Index (NDVI) over the Indian subcontinent in May was significantly correlated to the decrease in Indian summer monsoon rainfall in July, for the period of 1982–2003. They explained that a reduced July surface temperature caused by increased vegetation leads to a reduced land-sea thermal contrast, therefore causing the monsoon circulation to weaken. Our result showing that a decrease in LAI over the Indian subcontinent led to a weakened summer monsoon appears to contradict their result. However, they examined an increase in NDVI induced by an increase in irrigation during 1982–2003. Thus, the changes in surface roughness in their study were not so large as in this study, where the historical land use change from forest to cropland was specified. In addition, their study covered a time scale of two decades, versus 150 years in our study. Therefore, their study was dominated by changes in the surface heat balance, resulting in a different response for the monsoon precipitation and circulation.

The coupling strength between the soil moisture and precipitation was examined by Koster et al. (2004), who conducted several boreal summer (JJA) simulations. They concluded that "hot spots," where the coupling strength between soil moisture and precipitation was strong, were located in transition zones between wet and dry climate. This was because evaporation was suitably high but still sensitive to soil moisture in those locations, and the atmosphere was amenable to the generation of precipitation.

The present study showed that soil moisture, evapotranspiration, and precipitation notably decreased during MAM due to LUCC in the IND region; these results agreed with one of the "hot spots" indicated in Koster et al. (2004). Voldire and Royer (2004) also showed that soil moisture and soil evaporation notably decreased during the dry season due to deforestation in an African region, which is another "hot spot." Moreover, Zhao et al. (2001) showed that over India (at a "hot spot"), latent heat flux significantly decreased during MAM due to LUCC, while it increased during other seasons. Thus, their results agreed with ours only during MAM. This disagreement in the results for all seasons except MAM was because the maximum decrease in LAI was much smaller in their study (0.13) than in ours (about 1.0). Findell et al. (2007) showed a decrease in latent heat flux during the wet season over northern India (not at a "hot spot") due to LUCC, also in agreement with our study. However, they showed no change during the dry season, as the ground was almost completely dried out. These previous studies implied that the impact of LUCC on the hydroclimate (i.e., changes in soil moisture, soil evaporation, and precipitation) during the dry season is greatest at the "hot spots" indicated by Koster et al. (2004).

5. Concluding remarks

This study investigated the impacts and mechanisms of how LUCC, from forest to cultivated land occurring between 1700 and 1850, affected the seasonal cycle of the hydroclimate over the IND and SCH regions. Takata et al. (2009) showed that the historical LUCC between 1700 and 1850 caused a reduction in summer (JJA) precipitation over these regions, with the decrease consistent with the monsoon rainfall trend obtained from proxy data. The present study further found that in the IND region, EFLUX decreased during most months in the year, in particularly during MAM after extended cultivation. However, in the SCH region, EFLUX discernibly decreased throughout the year. The varying impacts of LUCC on EFLUX during MAM between the IND and SCH regions could be explained by the different responses of EBFLUX induced by the unequal rainfall amounts during the dry season in the two regions. Namely, the LAI decrease due to LUCC would generally cause an increase in EBFLUX; however, the very low rainfall throughout the dry season in the IND region induced very low soil moisture and hence a reduction in EBFLUX. In contrast, the precipitation from March to April in the SCH region decreased by 1 mm day^{-1} due to a decrease in water vapor flux convergence, although EFLUX did not notably decrease during the same period. This is because the precipitation in the spring over the SCH region from March to April is influenced by broad-scale atmospheric circulation, i.e., the westerly wind regime.

Consequently, it has been shown that the decreases in precipitation, evapotranspiration, and soil moisture were induced throughout the year by the historical LUCC, and that they were remarkable in the spring in the IND region where there is a strong contrast between the dry and wet seasons. The regions with (without) such a strong coupling between precipitation and soil moisture agreed (did not agree) with the "hot spots" of strong land-atmosphere coupling (Koster et al. 2004). These "hot spots" have appeared in the transition zones between wet and dry climates, both in this study using the historical LUCC and in previous studies using an extreme LUCC. This implies that the impact of LUCC on the hydroclimate is high at the "hot spots". The impact of the historical LUCC between 1700 and 1850, and the associated changes in the surface energy/water balance and precipitation on the seasonal cycle of the Asian monsoon (including atmospheric circulation) will be discussed in another paper.

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