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Key Points:

- Simulations show a warming-induced northwestward shift of the Asian summer monsoon, which are consistent with geological records
- The western Pacific subtropical high intensified and expanded in response to past global warming
- The intertropical convergence zone (ITCZ) moved north (south) over the Indian (West Pacific) Ocean in a warmer world

Supporting Information:

Supporting Information may be found in the online version of this article.

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Warming-Induced Northwestward Migration of the Asian Summer Monsoon in the Geological Past: Evidence From Climate Simulations and Geological Reconstructions

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Abstract The cold and warm intervals during the Plio-Pleistocene provide an opportunity to assess the response of the Asian summer monsoon (ASM) to different levels of global warming. In this study, the northern edge of the ASM, a sensitive indicator of the advance and retreat of the ASM rain belt, was analyzed using climate outputs from PMIP3 and PlioMIP1, for the Last Glacial Maximum (LGM, ∼21,000 yr BP), the preindustrial, the mid-Holocene (∼6,000 yr BP), and the mid-Pliocene (∼3.3–3.0 Ma), among which the global temperature increased sequentially. The results show that the northern edge of the ASM migrated northwestward by ∼200 km, ∼50 km, and ∼50 km with global warming from the LGM to preindustrial, from the preindustrial to mid-Holocene, and from the mid-Holocene to mid-Pliocene, respectively. These results are generally consistent with geological records. The simulations show that the western Pacific subtropical high (WPSH) intensified and expanded geographically, and the intertropical convergence zone (ITCZ) migrated northward over the Indian Ocean and was shifted southward over the western Pacific. This led to a northwestward shift of the Asian monsoonal rain belt, and consequently to wetter conditions in India and northern China. During the mid-Pliocene, pronounced warming substantially intensified the WPSH, leading to the suppression of moisture transport from the Indian Ocean to southern China and the Indo-China Peninsula. Our results suggest that if the planet returns to a Pliocene warm world, precipitation will increase in northern China, while southern China and the Indo-China Peninsula will experience more frequent droughts.

1. Introduction

The Asian summer monsoon (ASM) sustains roughly 60% of the global population (Li et al., 2016) and serves as the main moisture supply for Asia (Webster et al., 1998). Meteorologists have shown that changes in the intensity of the ASM are reflected by the advance and retreat of the monsoon frontal rain belt. It is generally accepted that the more northerly the penetration of the frontal rain belt, the greater the intensity of the summer monsoon (Tao & Chen, 1987). The northern edge of the ASM, defined as the northern limit of the monsoon precipitation (Chen et al., 2018; Hu & Qian, 2007) and geographically parallel to the wet–dry transitional area (Qian et al., 2009), delineates the advance and retreat of the summer monsoon rain belt (Lan et al., 2020; Yang et al., 2015). However, in recent years the impact of global warming and associated ice loss in polar regions on the northern edge of the ASM has been debated (Severinghaus, 2009), with contradictory conclusions regarding the northward advance or southward retreat of the ASM (Endo et al., 2018; Hu & Qian, 2007; Jiang et al., 2019; Li et al., 2010).

Changes in the northern edge of the ASM during cold and warm periods in the geological past can provide insights into future monsoon changes caused by global warming. The Last Glacial Maximum (LGM, ∼21,000 yr BP), the preindustrial, the mid-Holocene (∼6,000 yr BP), and the mid-Pliocene (∼3.0–3.3 Ma) have been widely studied (Abell et al., 2021; Cao et al., 2019; Haywood et al., 2016; Marcott et al., 2013;

Table 1
Atmospheric CO_2 Concentrations and Global Mean Air Temperature for the LGM, the Pre-Industrial, the Mid-Holocene, and the Mid-Pliocene

	LGM	Pre-Industrial	Mid-Holocene	Mid-Pliocene	References
Atmospheric CO_2 concentrations	~185 ppmv	280 ppmv	~280 ppmv	400–450 ppmv	Lüthi et al., 2008; Lunt et al., 2012; Pagani et al., 2010; Yang et al., 2018
Global mean air temperature compared with today	~5°C lower	~0.8°C–1.2°C lower	~0.7°C higher	~1.9°C–3.6°C higher	Chang, 2018; Hansen et al., 2006; Intergovernmental Panel on Climate Change, 2013; Marcott et al., 2013

Otto-Bliesner et al., 2006; Shakun et al., 2012; Wang et al., 2019). These four periods exhibited similar Tibetan Plateau topography, but with different global temperature and atmospheric CO_2 concentration (Table 1), thus providing an opportunity to comprehensively analyze the response of the ASM northern edge to different degrees of global warming and the resulting melting of polar ice.

Numerical experiments have emerged as an efficient means of understanding past climates on regional and global scales. As abundant geological data are available for the mid-Holocene, LGM, and the mid-Pliocene, many paleoclimate simulations targeting these time slices have been conducted. Based on preindustrial control experiments and simulations of the LGM and the mid-Holocene climate within the framework of the Paleoclimate Model Intercomparison Project (PMIP), and of the mid-Pliocene climate within the framework of the Pliocene Model Intercomparison Project (PlioMIP1), the large-scale features of global and regional climate change have been widely analyzed (e.g., Braconnot et al., 2007; Dowsett et al., 2013; Jiang et al., 2015; Kageyama et al., 2012; Koenig et al., 2015; Roche et al., 2012; Zhang et al., 2013). Although the northern edge of the ASM during the mid-Pliocene has been analyzed (Huang et al., 2019), its characteristics and dynamic mechanisms during different warm intervals are not fully understood. Here we use output data derived from the PMIP3 and PlioMIP1 climate models to comprehensively analyze the behavior of the northern edge of the ASM. We then compare the simulations with geological records and address the possible mechanisms responsible for the migration of the northern edge of the ASM under different global warming levels.

2. Data and Methods

This study considers simulations of the LGM and mid-Holocene climates using coupled ocean–atmosphere general circulation models (AOGCMs) carried out within the PMIP3 framework (Table S1); while the mid-Pliocene climates are derived from two types of experiment within the PlioMIP1 framework: atmosphere-only general circulation models (AGCMs) and coupled atmosphere-ocean general circulation models (AOGCMs) (Table S2). AGCMs run with fixed SSTs and sea-ice, while AOGCMs predict SSTs and sea-ice. Therefore, outputs of the AOGCMs from the PMIP3 and PlioMIP1 were used in this study. The boundary conditions for the PMIP3 and PlioMIP1 experiments are listed in Tables 2 and 3, respectively. Further details of the boundary conditions and experimental design for PMIP3 can be found in Braconnot et al. (2012) and Taylor et al. (2012), or at http://pmip3.lsce.ipsl.fr/; and details for PlioMIP1 can be found in Haywood et al. (2010, 2011) and Dowsett et al. (2010), or at http://geology.er.usgs.gov/eespteam/prism/prism_pliomip.html.

The most significant differences among the boundary conditions for the LGM, preindustrial, mid-Holocene, and mid-Pliocene simulations are as follows: (a) Atmospheric CO_2 concentration. Its value for the LGM, preindustrial, mid-Holocene, and mid-Pliocene was set to 185 ppmv, 280 ppmv, 280 ppmv, and 405 ppmv, respectively. (b) Changes in Earth orbital parameters. Compared to the preindustrial, the summer insolation at northern high latitudes increased by ~5% for the mid-Holocene, and decreased slightly during the LGM, while the insolation value for the mid-Pliocene was the same as that of the preindustrial. (c) Ice sheet volume and extent. Compared to the preindustrial, the polar ice sheets expanded extensively during the LGM and decayed substantially during the mid-Pliocene, while the mid-Holocene ice volume was the same as during the preindustrial.

Table 2
The Boundary Conditions for the Mid-Holocene (6 ka) and LGM (21 ka) in the PMIP3

	Mid-Holocene	LGM
Orbital parameters	Eccentricity = 0.018682; Obliquity = 24.105°; Precession-180° = 0.87°	Eccentricity = 0.018994; Obliquity = 22.949°; Precession-180° = 114.42°
Trace gases	CO_2 = 280 ppm; CH_4 = 650 ppb; N_2O = 270 ppb; CFCs = 0; O_3 = same as in pre-industrial	CO_2 = 185 ppm; CH_4 = 350 ppb; N_2O = 200 ppb; CFCs = 0; O_3 = same as in pre-industrial
Aerosols	Same as in pre-industrial	Same as in pre-industrial
Solar constant	Same as in pre-industrial	Same as in pre-industrial
Vegetation	Prescribed or interactive as in pre-industrial	Same as in pre-industrial
Ice sheets	Same as in pre-industrial	Averaging three different ice sheets reconstructions: ICE-6G v2.0, MOCA and ANU
Topography and coastlines	Same as in pre-industrial	pmip3_21k_sftlf_v0; pmip3_21k_orog_diff_v0

Different models may have different responses to the same external forcings, such that the simulated results may have model dependence. A multi-model ensemble (MME) can reduce the model biases (Yan et al., 2018), and has been widely used to analyze climate changes (Kageyama et al., 2021; Saito et al., 2013; Yan et al., 2018). In this study, all analyses were performed using the multi-model ensemble mean (MME). Not all AOGCMs for the mid-Pliocene have water vapor flux data available, and therefore this variable was calculated using a four-model ensemble mean (CCSM4-AOGCMs, GOALS-g2-AOGCMs, MIROC4m-AOGCMs, and NorESM-L-AOGCMs). In addition, we adopted the northern boundary of the monsoon area as the northern edge of the ASM, following the definition that the summer monsoon area is the region where the local summer (May–September) minus winter (November–March) precipitation rate exceeds 2 mm day^{-1}, and the local summer precipitation exceeds 55% of annual precipitation (Wang et al., 2012).

The paleoclimates and paleoenvironments of the LGM, mid-Holocene and mid-Pliocene have been studied extensively using a variety of proxies, including paleontological indicators, geochemical proxies, and physical indicators, which constitute the primary basis for reconstructions of dry–wet conditions. In order to reduce uncertainties derived from multiple interpretations of various paleoclimatic proxies, paleoclimatic

Table 3
The Boundary Conditions for the Mid-Pliocene (3.0–3.3 Ma) in the PlioMIP1

	Atmosphere-only general circulation models (AGCMs)		Coupled ocean–atmosphere general circulation models (AOGCMs)	
SSTs	fixed SSTs		predict SSTs	
	The same boundary conditions between AGCMs and AOGCMs			
	Land-sea mask	Topography	Ice sheet	Vegetation
Prefered boundary conditions	PRISM3D (land_fraction_v1.1)	PRISM3D (topo_v1.1*)	PRISM3D (biome_veg_v1.3 or mbiome_veg_v1.3)	PRISM3D (biome_veg_v1.3 or mbiome_veg_v1.3)
Alternate boundary conditions	Modern	PRISM3D (topo_v1.4*)	PRISM3D (biome_veg_v1.2 or mbiome_veg_v1.2)	PRISM3D (biome_veg_v1.2 or mbiome_veg_v1.2)

	CO_2	N_2O	CH_4	CFCS	O_3
Trace gases	405 ppmv	Same as in pre-industrial	Same as in pre-industrial	Same as in pre-industrial	Same as in pre-industrial
Solar constant					Same as in pre-industrial
Aerosols					Same as in pre-industrial
Orbital parameters					Same as in pre-industrial

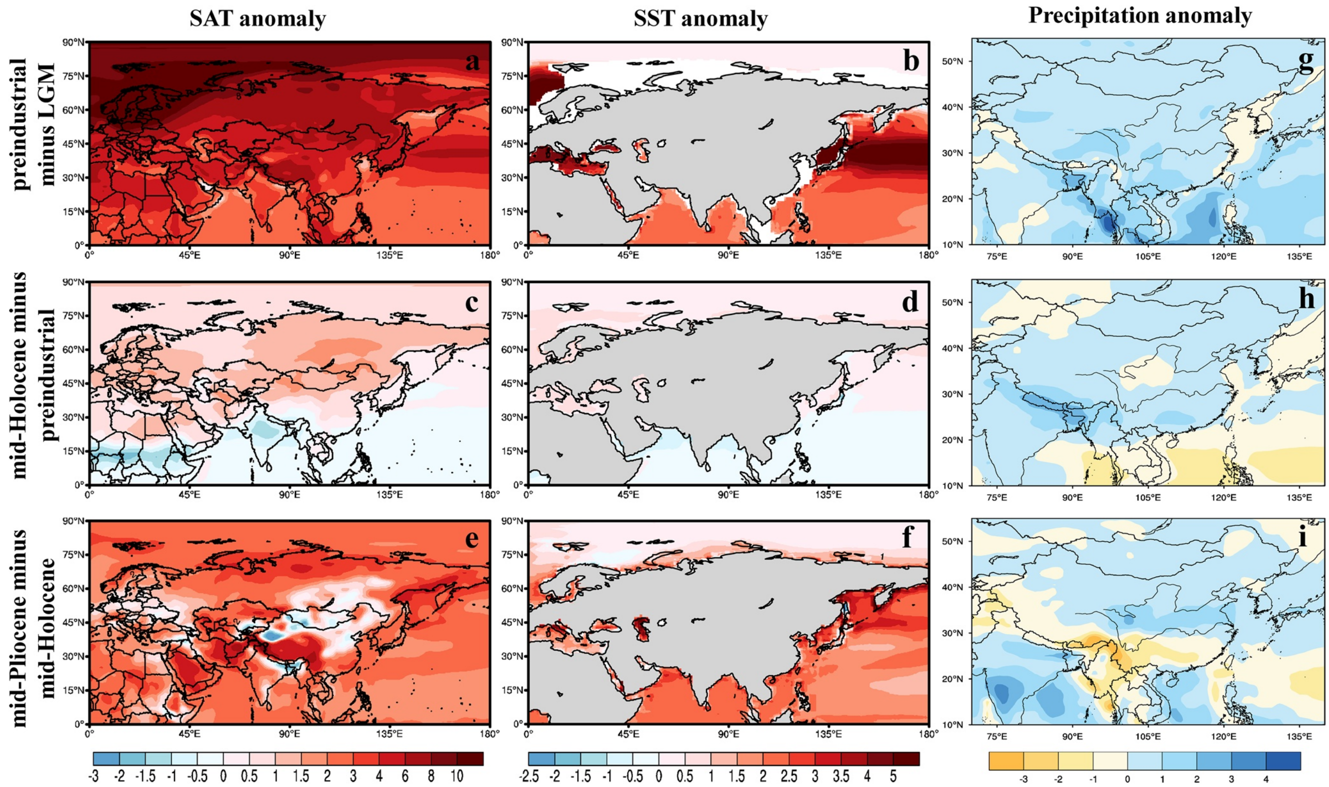

Figure 1. Multi-model ensemble (MME) for summer mean surface air temperature (SAT, units: °C), summer mean sea surface temperature (SST, units: °C), and summer mean precipitation (units: mm day^{-1}) anomalies between the Last Glacial Maximum (LGM), preindustrial, mid-Holocene, and mid-Pliocene. Summer spans May–September (MJJAS) and winter spans November–March (NDJFM) for the Northern Hemisphere.

records based on paleontological indicators (sporopollen, plant macrofossils, ostracoda, and fauna; Tables S3–S5), which are robust measures of paleomonsoon intensity, were assembled.

3. Results

3.1. Temperature and Precipitation Anomalies Between the LGM, Preindustrial, Mid-Holocene, and Mid-Pliocene

The MME results show that, with respect to the LGM, the summer surface air temperature (SAT) in the preindustrial was substantially warmer (~7°C) at northern high latitudes, while the low-latitude SAT increased by 2°C–3°C (Figure 1a); and the summer SAT was ~5°C warmer in Eurasia during the preindustrial (Figure 1a), while the sea surface temperatures (SSTs) of the South China Sea and the equatorial western Pacific were ~2°C higher (Figure 1b). Compared with the preindustrial, the mid-Holocene SAT increased by ~1°C at northern high latitudes, while the low-latitude SAT decreased by 0.5°C (Figure 1c). Moreover, the summer SAT in the Eurasia mainland increased by ~1.5°C during the mid-Holocene (Figure 1c), while the SSTs of the South China Sea and the equatorial western Pacific cooled by ~0.5°C (Figure 1d). With respect to the mid-Holocene, the increased summer SAT in the mid-Pliocene at northern high latitudes (~1.5°C–3°C) was slightly higher than at low latitudes (~1°C–2°C; Figure 1e). The summer SAT in the mid-Pliocene was ~3°C warmer in Eurasia (Figure 1e), while SSTs in the South China Sea and the equatorial western Pacific were ~1.5°C higher in the mid-Pliocene than in the mid-Holocene (Figure 1f). Apparently, the meridional temperature gradient between high and low latitudes decreased, and the thermal contrast between Eurasia and the equatorial western Pacific was enhanced with increasing global temperature.

The numerical simulations show that the summer MME precipitation increased in most areas of Asia during the preindustrial, relative to the LGM, as well as during the mid-Holocene, relative to preindustrial. The former simulation (the preindustrial relative to the LGM) showed significantly increased precipitation

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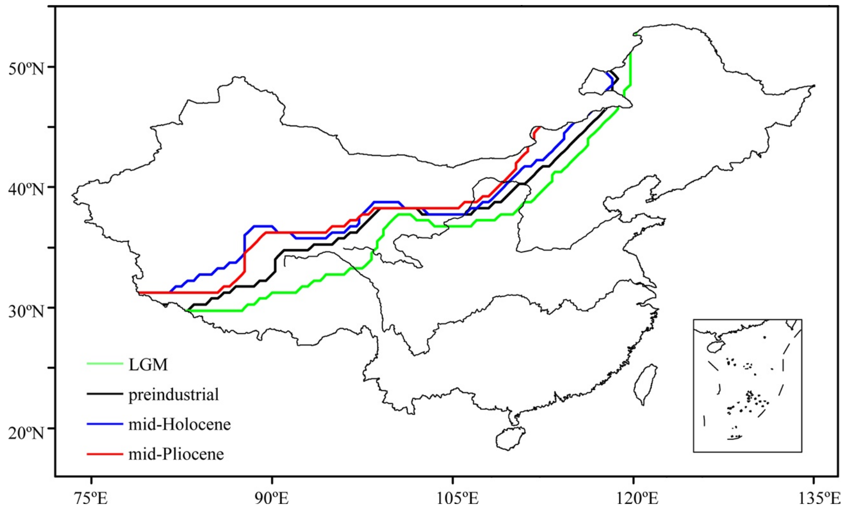

Figure 2. The northern edge of the Asian summer monsoon (ASM) for the Last Glacial Maximum (LGM) (green line), the preindustrial (thick black line), the mid-Holocene (blue line), and the mid-Pliocene (red line).

of ~0.5–1.5 mm day^{-1} in the Asian continent (Figure 1g), while the latter (the mid-Holocene relative to preindustrial) exhibited increased precipitation of ~0.5–1 mm day^{-1} in India and China (Figure 1h). During the mid-Pliocene, with respect to the mid-Holocene, precipitation increased significantly in India and northern China (0.5–1.5 mm day^{-1}), but decreased slightly in southern China (0–1 mm day^{-1}; Figure 1i), and significantly in the Indo-China Peninsula (1–2.5 mm day^{-1}; Figure 1i). The annual precipitation anomalies (Figure S1) show similar patterns as seen in summer precipitation anomalies. The winter precipitation increased in most areas of Asia during the preindustrial, relative to the LGM, as well as during the mid-Pliocene, relative to mid-Holocene, while decreased in most areas of Asia during the mid-Holocene, relative to the preindustrial (Figure S1).

3.2. The Northern Edge of the ASM During the LGM, Preindustrial, Mid-Holocene, and Mid-Pliocene

The northern edge of ASM was analyzed systematically, based on the definition mentioned in Data and Methods section. As shown in Figure 2, during the four periods, the northern edge of the ASM moved northwestward with global warming, although the scale of the migration varies with different degrees of global warming. A large northwestward shift (~200 km) of the ASM northern edge was evident during the preindustrial relative to LGM, while a small northwestward shift (~50 km) of the edge is simulated in the mid-Holocene compared with the preindustrial. In addition, with respect to the mid-Holocene, the mid-Pliocene ASM northern edge shifted northwestward by ~50 km over the region east of 100°E, while its location was almost the same during the two intervals over the region west of 100°E.

3.3. Data-Model Comparison

We compiled three paleontological datasets covering the whole of China to examine the spatial climatic patterns for the LGM, mid-Holocene, and mid-Pliocene (Figures 3a–3c; Tables S3–S5). The three datasets represent three key time windows: 18,000–24,000 yr BP for the LGM, 5,000–7,000 yr BP for the mid-Holocene, and 3.0–3.3 Ma for the mid-Pliocene. The LGM data set contains 75 records (Figure 3b), of which 27 sites were humid and 48 sites were dry. For the mid-Holocene, 227 records were compiled (Figure 3a), which included 175 humid sites and 52 dry sites. The mid-Pliocene data set contains 50 sites throughout China (Figure 3c), among which 15 sites were dry and 35 sites were humid. The three time periods show a spatial climatic pattern similar to the present day, with dry conditions in northwestern China and humid conditions in southeastern China.

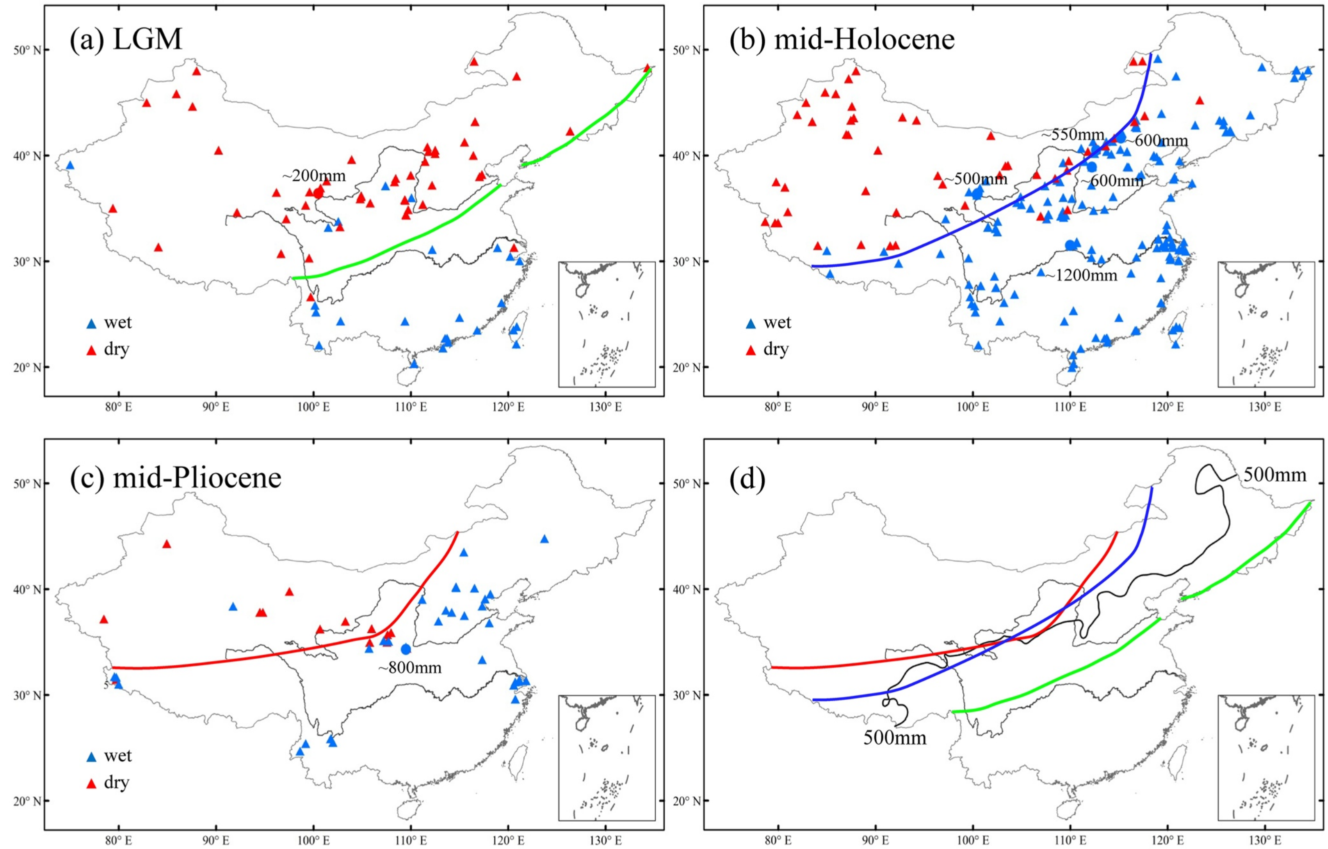

Figure 3. Reconstructed wet–dry boundary for the Last Glacial Maximum (LGM) (a, d; green lines), the mid-Holocene (b, d; blue lines), and the mid-Pliocene (c, d; red lines), and comparison with the present-day (d; thick black line). The wet sites are in blue and the dry sites are in red (a–c); solid circles indicate sites with a quantitative annual precipitation reconstruction (adjacent) based on pollen records. The mid-Pliocene records (c) are updated from Huang et al. (2019), and detailed information on all of the records can be found in the supplementary data (Tables S3–S5). The thick black line (d) represents the 500-mm isoline of annual precipitation (1981–2010, provided by the US Center for Climate Prediction; Xie and Arkin, 1997), which is the present-day boundary between humid–subhumid and arid–semiarid areas.

At present, the 500-mm isoline of annual precipitation marks the boundary between humid-subhumid and arid-semiarid areas (Figure 3d; Sun & Wang, 2005). The distribution of modern vegetation zones shows that the areas to the north of the 500-mm isoline are dominated by steppe or desert–steppe, while those to the south of the boundary are dominated by forest (Sun & Wang, 2005). Therefore, pollen records are an effective approach for reconstructing the wet–dry boundary in the geological past. During the three geological time periods, the location of the wet–dry boundary, which was reconstructed based on paleontological records, was supported by several precipitation estimates based on pollen records (Figures 3a–3c). During the LGM, pollen records from Lake Qinghai, located on the dry side of the reconstructed wet–dry boundary, indicated an annual precipitation as low as ∼200 mm (Li et al., 2017). For the mid-Holocene, reconstructions from four pollen sites (Daihai, Gonghai, Bayanchagan, and Qinghai) near the wet–dry boundary showed an annual precipitation of ∼500–600 mm (Chen et al., 2015; Jiang et al., 2006; Li et al., 2017; Xu et al., 2010); while at Dajiuhu, located in the wet region and far from the reconstructed wet–dry boundary, annual precipitation of as high as ∼1,200 mm was derived from the pollen record (Sun et al., 2019). During the mid-Pliocene, the Changgoucun pollen site had a reconstructed annual precipitation of ∼800 mm (Wang et al., 2019). Clearly, the reconstructed location of the wet–dry boundary, that is, the northern edge of the ASM, was displaced northwestwards by ∼350, ∼100, and ∼150 km with global warming, from the LGM to the present, from the present to mid-Holocene, and from the mid-Holocene to the mid-Pliocene, respectively.

The northwestward shift of the northern edge of the ASM captured by the models (Figure 2) is roughly consistent with the geological records (Figure 3d); however, there are differences in detail between the simulations and reconstructions. The geological records show a greater magnitude shift of the ASM

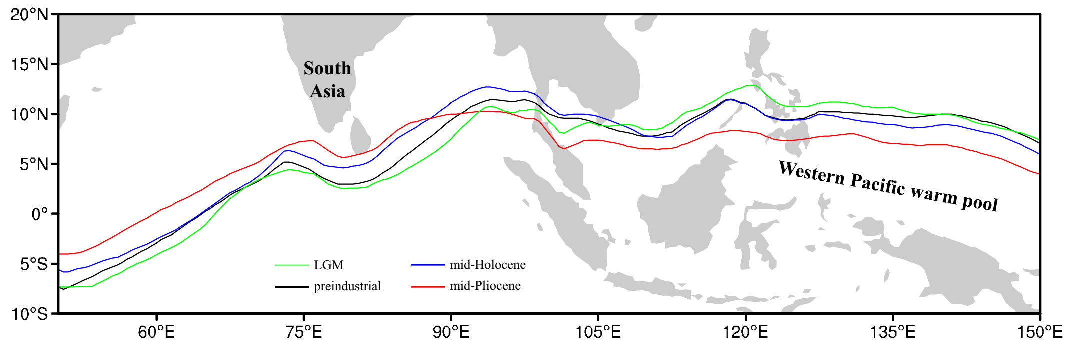

Figure 4. Summer location of the Intertropical Convergence Zones (ITCZ) during the Last Glacial Maximum (LGM) (green line), the preindustrial (black line), the mid-Holocene (blue line), and the mid-Pliocene (red line).

(∼350 km) at present relative to the LGM, while the simulations show a ∼200 km northwestward migration from the LGM to preindustrial. Moreover, the geological records show a greater shift of the wet–dry boundary at the northeastern and southwestern ends of the boundary during the mid-Pliocene compared to the mid-Holocene, while the simulations show a northwestward shift of the edge only over the region east of 110°E. It follows that, except for the north–south climatic contrast, a distinct enhanced east–west contrast is evident in geological records during the mid-Pliocene. In addition, in southern China, all geological sites show wet conditions during the mid-Pliocene, while the simulations show a slight decrease in precipitation (Figure 1i). As the mid-Pliocene geological records are sparse and clustered in the eastern and western ends of southern China, more robust geological reconstructions from across southern China are needed in future studies.

4. Mechanism for ASM Changes During Past Global Warming

During the Plio-Pleistocene, atmospheric CO_2 concentration and solar insolation are thought to be the primary factors affecting global temperature (Intergovernmental Panel on Climate Change, 2013; Lacis et al., 2010; Royer, 2006; Sackmann & Boothroyd, 2003). Although atmospheric CO_2 levels and Northern Hemisphere summer insolation both increased from the LGM to Holocene, numerous studies have demonstrated a dominant contribution of the rise in atmospheric CO_2 to the last deglacial warming of ∼6°C (Cao et al., 2019; Shakun et al., 2012). Likewise, the 2°C global warming during the mid-Pliocene was unambiguously ascribed to increased CO_2 concentrations (Foster & Rohling, 2013; Marcott et al., 2013). These CO_2-induced warmings would have affected the ASM via changing the position and strength of the atmospheric circulation and increasing the water vapor supply.

4.1. Changes in the ITCZ and WPSH

The ASM is composed of two primary subsystems: the South Asian (Indian) summer monsoon and the East Asian summer monsoon (EASM; Wang et al., 2003). Previous studies (Wang et al., 2003) have shown that, in the South Asian monsoon domain (40°E–105°E), the summer monsoon is mainly controlled by the tropical climate system, while in the East Asian monsoon domain (105°E–160°E), the summer monsoon is controlled by both the subtropical and tropical climate systems.

The South Asian monsoon results from a seasonal shift in the Intertropical Convergence Zones (ITCZ) (Gadgil, 2003; Wang & Ding, 2009). In order to analyze changes in the ITCZ among the LGM, preindustrial, mid-Holocene, and mid-Pliocene, we calculated the ITCZ location, defined as the latitude corresponding to the centroid of the area-integrated precipitation from 20°S to 20°N (Donohoe et al., 2013). The results (Figure 4) show that over South Asia, the ITCZ shifted northward with global warming from the LGM to preindustrial, from the preindustrial to mid-Holocene, and from the mid-Holocene to the mid-Pliocene, which is consistent with the northward displacement of the ASM northern edge (Figure 2). In contrast, over the western Pacific warm pool region, the ITCZ shifted southward with global warming from the LGM

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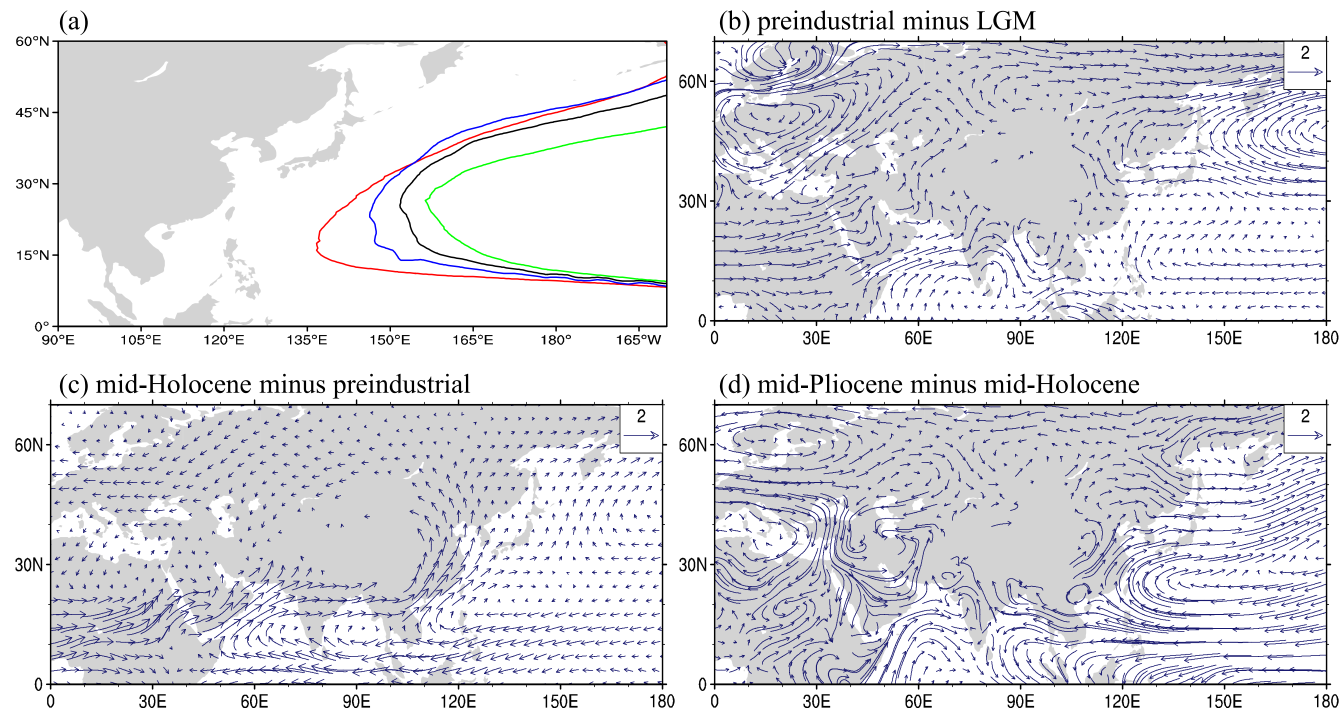

Figure 5. (a) Zero contour lines of the 850-hPa eddy geopotential height field for the Last Glacial Maximum (LGM) (green), preindustrial (black), mid-Holocene (blue), and mid-Pliocene (red), and summer wind field (m s^{-1}) anomalies for (b) preindustrial relative to the LGM, (c) mid-Holocene relative to the preindustrial, and (d) mid-Pliocene relative to the mid-Holocene.

to preindustrial, from the preindustrial to mid-Holocene, and from the mid-Holocene to the mid-Pliocene, whereas the ASM northern edge migrated northward (Figure 2).

Modern meteorological observations have shown that poleward air flow along the western flank of the western Pacific subtropical high (WPSH) is a major component of the EASM (Huang et al., 2019; Lu & Dong, 2001), and thus the advance and retreat of the EASM are closely related to the activity of the WPSH. The position of the WPSH is conventionally measured by the 5,870/5,880-gpm contour line in the 500-hPa geopotential height field (Gong & Ho, 2002; Zhou & Li, 2002). However, using the geopotential height itself to investigate changes in the WPSH could be affected by artificial trends of the lifted isobaric surface at middle and low latitudes and its exacerbated effects with increasing geopotential height under global warming (Lu et al., 2008; Yang & Sun, 2003). To minimize this effect, we used the 0-gpm contour lines of the 850-hPa eddy geopotential height (i.e., the anomaly between the 850-hPa geopotential height and the zonal mean of the 850-hPa geopotential height [Huang et al., 2015]), to investigate the position of the WPSH during the LGM, preindustrial, mid-Holocene, and mid-Pliocene. The results show that the WPSH expanded with global warming, from the LGM to preindustrial, from the preindustrial to mid-Holocene, and from the mid-Holocene to the mid-Pliocene (Figure 5a).

Additionally, the MME summer wind anomalies at 850 hPa exhibit an anticyclonic circulation pattern across the region from 105°E to the western Pacific during the preindustrial (relative to LGM), the mid-Holocene (relative to preindustrial), and the mid-Pliocene (relative to mid-Holocene) (Figures 5b–5d), indicating a significantly enhanced WPSH and associated southeasterly winds with global warming. The expansion and intensification of the WPSH both led to the northwestward shift of the northern edge of the ASM and the southward movement of the ITCZ over the East Asian domain. Recently, some researchers emphasized the role of interactions between the westerlies and the ASM in determining the rainfall in the Yangtze River Valley (Chiang et al., 2017; Kong & Chiang, 2020; Sampe & Xie, 2010). However, the effect of the westerlies on the northeastern ends of the ASM edge, which is located far north of the Yangtze River Valley, remains unclear. Furthermore, the location of the southwestern end of the ASM edge is controlled mainly by the Indian monsoon (Wang et al., 2014; Yim et al., 2014), but shows the same migration pattern (Figure 2) as

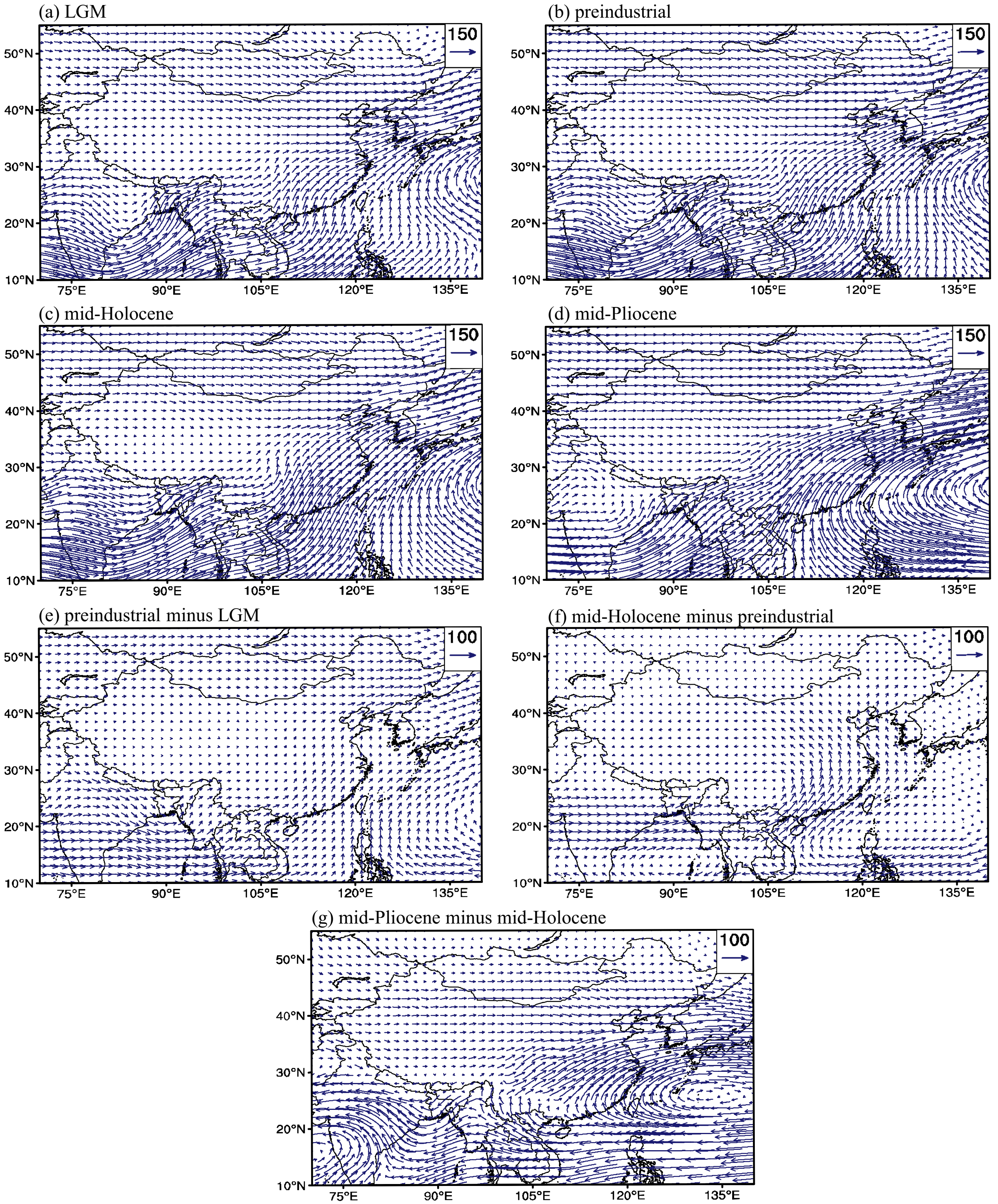

Figure 6. Vertically integrated water vapor flux (arrows, units: kg m^{-1} s^{-1}) for (a) the Last Glacial Maximum (LGM), (b) the preindustrial, (c) the mid-Holocene, and (d) the mid-Pliocene, and the anomalies (arrows, units: kg m^{-1} s^{-1}) for (e) the preindustrial relative to the LGM, (f) the mid-Holocene relative to the preindustrial, and (g) the mid-Pliocene relative to the mid-Holocene.

the northeastern end of the edge. In this context, the northern edge of the ASM is controlled mainly by the changes in the ASM intensity

4.2. Changes in Water Vapor Flux

To further investigate the mechanism responsible for the changes of the ASM during the LGM, preindustrial, mid-Holocene, and mid-Pliocene, we analyzed the summer water vapor flux for the four time slices. The results show that two air flows, namely the southwesterly and southeasterly flows, are responsible for the transport of water vapor to mainland China (Figures 6a–6d). The southwesterly flow originated in the Indian Ocean and passed through the Bay of Bengal and the Indo-China Peninsula, and the southeasterly flow came from the South China Sea and the West Pacific. The water vapor flux from the southwest and southeast both increased during the preindustrial (relative to the LGM; Figure 6e), as well as during the mid-Holocene (relative to preindustrial; Figure 6f), in response to the expansion and intensification of the WPSH and the northward shift of the ITCZ over the South Asian sector. Compared to the mid-Holocene, the water vapor flux from the southeast further increased during the mid-Pliocene. However, strong anomaly vectors from east to west appeared over the South China Sea, Indo-China Peninsula, and the Bay of Bengal during the mid-Pliocene (Figure 6g), indicating a substantially decreased water vapor supply from the Indian Ocean to southern China and the Indo-China Peninsula; this is evidently responsible for the slight decrease in precipitation in these regions (Figure 1i). In this context, we suggest that during the mid-Pliocene, the pronounced warming, especially over the Tibetan Plateau (Duan et al., 2017; Li et al., 2011), substantially intensified the WPSH, thereby leading to a suppressed moisture transport from the Indian Ocean, and a resulting slightly drier southern China and the Indo-China Peninsula. Modern meteorological observations have shown that frequent droughts occur in southern China and the Indo-China Peninsula with global warming (Miyan, 2015; Wang et al., 2016), which may result from to the exceptionally enhanced WPSH induced by strong heating over the Tibetan Plateau (Duan et al., 2017; Li et al., 2011). These droughts may serve as modern examples of the mid-Pliocene global warming.

5. Conclusions

The simulation results show that the northern edge of the ASM generally exhibited a northwestward shift of ~200, ~50, and ~50 km with global warming from the LGM to preindustrial, from the preindustrial to mid-Holocene, and from the mid-Holocene to the mid-Pliocene, respectively. Additionally, the geological records show respective northwestward migrations of ~350, ~100, and ~150 km for the dry–wet boundary. The simulation and reconstruction results consistently indicate a northwestward advance of the ASM rain belt with global warming. Accordingly, summer precipitation increased in most areas of China from the LGM to preindustrial, as well as from the preindustrial to the mid-Holocene; while during the mid-Pliocene relative to the mid-Holocene, precipitation increased significantly in northern China, but decreased slightly in southern China and the Indo-China Peninsula.

The simulations also show a substantial increase in the thermal contrast between the Asian mainland and the equatorial western Pacific with global warming. In this scenario, the WPSH intensified and expanded, and the ITCZ migrated northward over the Indian Ocean and was shifted southward over the Western Pacific, thereby leading to the northwestward advance of the ASM and associated rain belt penetration into northern China. During the mid-Pliocene, the pronounced global warming substantially intensified the WPSH, leading to the suppressed moisture transport from the Indian Ocean. As the mid-Pliocene is an analogue for near-future warming, we suggest that in the future, northern China will become wet, and southern China and the Indo-China Peninsula will become slightly dry and experience more frequent droughts.

Data Availability Statement

The PlioMIP data are described at https://geology.er.usgs.gov/egpsc/prism/prism_1_23/prism_pliomip_data.html. The PMIP3 data are available at https://esgf-node.llnl.gov/search/cmip5/. The CMAP precipitation data used in this study are available online at the following URL: https://www.esrl.noaa.gov/psd/data/gridded/data.cmap.html.

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