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#### **Key Points:**

- Simulations show a ~150km-northwestward migration of the East Asian summer monsoon (EASM) during the mid-Pliocene warm period
- The western Pacific subtropical high (WPSH) intensified and extended westward
- An enhanced east-west climatic contrast during the mid-Pliocene was observed in geological records compared with simulations

#### Correspondence to:

S. Yang, yangsl@mail.iggcas.ac.cn

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# Northwestward Migration of the Northern Edge of the East Asian Summer Monsoon During the Mid-Pliocene Warm Period: Simulations and Reconstructions

Xiaofang Huang<sup>1,2,3</sup>, Dabang Jiang<sup>3,4,5</sup>, Xinxin Dong<sup>6</sup>, Shiling Yang<sup>1,2,3</sup>, Baohuang Su<sup>4</sup>, Xiangyu Li<sup>4</sup>, Zihua Tang<sup>1,2</sup>, and Yongda Wang<sup>1,2,3</sup>

<sup>1</sup>Key Laboratory of Cenozoic Geology and Environment, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China, <sup>2</sup>CAS Center for Excellence in Life and Paleoenvironment, Beijing, China, <sup>3</sup>College of Earth and Planetary Sciences, University of Chinese Academy of Sciences, Beijing, China, <sup>4</sup>Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China, <sup>5</sup>Joint Laboratory for Climate and Environmental Change, Chengdu University of Information Technology, Chengdu, China, <sup>6</sup>Bureau of General Affairs, Chinese Academy of Sciences, Beijing, China

**Abstract** The mid-Pliocene (~3.3–3.0 Ma) was the most recent warm interval during which atmospheric CO<sub>2</sub> concentrations were similar to the present level of ~400 ppmv. Therefore, it is often regarded as an analog for a near-future climate scenario. To examine the behavior of the East Asian summer monsoon (EASM) during the mid-Pliocene warm period, the northern edge of the EASM, a sensitive indicator of the advance and retreat of the summer monsoon rainbelt, was analyzed using the output of the Pliocene Model Intercomparison Project Phase 1. The results show a ~150-km-northwestward migration of the northern edge of the EASM during the mid-Pliocene compared to the preindustrial period, which is consistent with that derived from a comparison of geological records and modern observations. However, the geological records indicate a greater east-west climatic contrast during the Pliocene than at present, which requires investigation in future modeling studies. The simulations also show a substantial increase in the large-scale land-sea thermal contrast between the East Asian mainland and the equatorial western Pacific during the interval of mid-Pliocene warmth. This led to the intensification and westward extension of the western Pacific subtropical high, causing a northwestward shift of the EASM and the resulting mitigation of drought in northern China. We suggest that global warming will shift the EASM northwestward mainly via changes in the position and intensity of the western Pacific subtropical high; this requires systematic studies in the future based on meteorological observations and simulations.

# 1. Introduction

The northern edge of the East Asian summer monsoon (EASM) is defined as the northern limit of the monsoon precipitation (Chen et al., 2018; Hu & Qian, 2007; Tang et al., 2007; Xu & Qian, 2003). It shifts northward or southward with interannual fluctuations of the EASM and thus forms the northern marginal zone of the EASM, which extends in a NE-SW direction and represents a distinctive boundary zone of monsoon expansion or contraction (Tang, Qian, et al., 2010; Zhu et al., 2018). At present, the northern marginal zone of the summer monsoon is the wet-dry transitional area in East Asia, as well as the farming-pastoral ecotone and the ecologically fragile zone (Qian et al., 2009; Yang et al., 2002).

Changes in the northern edge of the EASM have been a major research focus for decades, because it sensitively records the advance and retreat of the summer monsoon rainbelt. The northern edge of the EASM gradually migrated southward with decreasing summer monsoon intensity during the past few decades (Hu & Qian, 2007; Li et al., 2010; Ma & Fu, 2003; Qian et al., 2009), which is attributed by some researchers to global warming. In contrast, several other studies have predicted an intensification of the EASM with global warming and thus a northward shift in the northern edge of EASM in the near future (Kripalani et al., 2007; Yang, Ding, et al., 2015). Atmospheric  $CO_2$  concentrations have now reached over 400 ppmv; however, the atmosphere-ocean system is still in a nonequilibrium state due to the large thermal inertia of the ocean, hindering predictions and projections of the EASM. Clearly, changes in the northern edge of EASM during warm climatic intervals in the geological past, during which greenhouse gases and

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Table 1

Basic Information on the General Circulation Models in the PlioMIP									
Model	Туре	Atmosphere resolution	Boundary conditions	Years for analyzing	References				
CAM3.1	AGCM	T42, L26	Alternate	30	Yan et al. (2012)				
CAM4	AGCM	T31, L26	Alternate	20	Zhang and Yan (2012)				
HadAM3	AGCM	2.5° × 3.75°, L19	Preferred	30	Bragg et al. (2012)				
ECHAM5	AGCM	T31, L19	Preferred	30	Stepanek and Lohmann (2012)				
LMDZ5A	AGCM	1.9° × 3.75°, L39	Alternate	30	Contoux et al. (2012)				
MIROC4m-AGCM	AGCM	T42, L20	Preferred	30	Chan et al. (2011)				
MIR-CGCM2.3-AGCM	AGCM	T42, L30	Alternate	50	Kamae and Ueda (2012)				
FGOALS-g2	AOGCM	$1^{\circ} \times 1^{\circ}$ , L30	Alternate	100	Zheng et al. (2013)				
GISS-E2-R	AOGCM	2° × 2.5°, L40	Preferred	30	Chandler et al. (2013)				
HadCM3	AOGCM	2.5° × 3.75°, L19	Alternate	50	Bragg et al. (2012)				
COSMOS	AOGCM	T31, L19	Preferred	30	Stepanek and Lohmann (2012)				
IPSLCM5A	AOGCM	1.9° × 3.75°, L39	Alternate	30	Contoux et al. (2012)				
MIROC4m	AOGCM	T42, L20	Preferred	30	Chan et al. (2011)				
MIR-CGCM2.3	AOGCM	T42, L30	Alternate	50	Kamae and Ueda (2012)				
CCSM4	AOGCM	$0.9^{\circ} \times 1.25^{\circ}$ , L26	Alternate	30	Rosenbloom et al. (2013)				
NorESM-L	AOGCM	T31, L26	Alternate	100	Zhang et al. (2012)				

*Note.* "Preferred" refers to a land/sea mask that has been entirely altered to meet the PlioMIP boundary conditions, whereas "alternate" is where modeling groups have had to use more similar to modern land/sea mask.

climate reached an equilibrium state, can provide insight into the possible response of the monsoon system to global warming and its mechanisms.

The mid-Pliocene warm period ( $\sim$ 3.3–3.0 Ma) is the most recent period of relatively warm and stable climate in Earth's history, during which atmospheric CO<sub>2</sub> concentrations were approximately 400–450 ppmv (Lunt et al., 2012; Pagani et al., 2010) and global mean annual temperature was 1.9–3.6 °C warmer than today (IPCC, 2013). This period is similar to today in terms of the continent-ocean configuration and atmospheric CO<sub>2</sub> concentrations (Haywood et al., 2016) and has often been proposed as a climatic analog for the end of the present century. The mid-Pliocene is presumably representative of a long-term environmental and climate equilibrium response to higher than preindustrial levels of CO<sub>2</sub>, while the preindustrial to modern climate trend is a transient surface climate response (Haywood, Ridgwell, et al., 2011). Therefore, differences in imposed Pliocene vegetation and ice sheets compared to the modern/near future could explain any difference between simulated Pliocene and predicted future responses in the EASM as well as its northern edge.

Numerical experiments are a useful means of understanding past climates on regional and global scales. Based on simulations of the mid-Pliocene climate within the framework of the Pliocene Model Intercomparison Project (PlioMIP), the large-scale features of global and regional climate change have been analyzed (Dowsett et al., 2013; Haywood et al., 2000; Jiang et al., 2005; Kamae et al., 2011; Koenig et al., 2015; Li et al., 2015; Zhang et al., 2013). However, the characteristics of the mid-Pliocene northern edge of EASM have yet to be studied. Here we first examined the climatological fields derived from the experiments of the 16 PlioMIP climate models and then selected 11 of them to comprehensively analyze the changes of the northern edge of the EASM. Finally, we compare the simulations with geological records and address the mechanisms for the migration of the northern edge of the EASM.

#### 2. Data and Methods

#### 2.1. PlioMIP Experimental Design

Two types of experiment were designed within the PlioMIP framework. Experiment 1 used atmosphere-only general circulation models (AGCMs), while experiment 2 used coupled atmosphere-ocean general circulation models (AOGCMs). In this study, the model results from seven AGCMs and nine AOGCMs in PlioMIP (Table 1) were first examined, and then 11 models were selected to analyze the northern edge of the EASM. Both experiments describe the model setup for preindustrial and mid-Pliocene simulations. The boundary conditions applied to all climate models of PlioMIP used the USGS Project known as PRISM3 (Pliocene Research Interpretation and Synoptic Mapping), which has generated boundary conditions including



**Figure 1.** Taylor diagrams showing normalized pattern statistics for temperature and precipitation in East Asia between preindustrial experiments and modern climate reanalysis. (a) Red, dark, and blue represent summer, winter, and annual temperature, respectively. (b) Red denotes the anomaly between summer and winter precipitation, and blue indicates annual precipitation. The reference (REF) usually represents observations. The standard deviation of the modeled field is the radial distance from the origin, and the RMSE is the distance to the point REF. Both are normalized by the observed standard deviation. The azimuthal position gives the spatial correlation coefficient. The multimodel ensemble (MME) means of the atmosphere-only general circulation models (AGCMs), atmosphere-ocean general circulation models (AOGCMs), and all the models are also indicated.

monthly sea surface temperatures (SSTs), sea-ice distributions, vegetation cover, sea level, ice sheet extent, and topography (Dowsett et al., 2010). AGCMs were forced with the prescribed mid-Pliocene SSTs and sea ice extents, while the SSTs and sea ice extents in AOGCMs were predicted dynamically by the models (Haywood et al., 2016). In both experiments 1 and 2, the mid-Pliocene atmospheric  $CO_2$  was set to 405 ppmv. All other trace gases were specified at preindustrial concentrations, and a modern orbital configuration was used (Haywood, Dowsett, et al., 2011). Further details of the boundary conditions and experimental design for the PlioMIP can be found in Haywood et al. (2010); Haywood, Dowsett, et al. (2011); and Haywood et al. (2016) or at http://geology.er.usgs.gov/eespteam/prism/prism\_pliomip.html.

#### 2.2. Definition of the Northern Edge of the EASM

There are several approaches to measuring the northern edge of the EASM: for example, using the mean pseudo-equivalent potential temperature combined with precipitation and wind field (Hu & Qian, 2007), using pentad-average precipitation (Tao & Yi, 1999), and using normalized precipitation (Tang, Chen, et al., 2010). However, these climatic parameters cannot be obtained directly from the PlioMIP output. In this study, we adopt the northern boundary of the monsoon area as the northern edge of the EASM, following the definition that the summer monsoon area is the region where the local summer minus winter precipitation rate exceeds 2 mm/day and the local summer precipitation exceeds 55% of annual precipitation (Liu et al., 2009; Wang et al., 2012).

#### 2.3. Evaluation of the PlioMIP Models

To evaluate the models' ability to simulate the northern edge of the EASM, we compared the results of modern climate reanalysis data with those from the preindustrial control simulation. The reanalysis data include precipitation data (1981–2010; Xie & Arkin, 1997) provided by the U.S. Center for Climate Prediction (CMAP) and ERA-Interim monthly average temperature data (1979–2008) provided by the European Meteorological Center (Berrisford et al., 2011). The spatial resolutions of CMAP precipitation and ERA-Interim temperature data are  $2.5^{\circ} \times 2.5^{\circ}$  and  $\sim 0.7^{\circ} \times 0.7^{\circ}$ , respectively. To quantify the details of the northern edge of the EASM, all model and reanalysis data were aggregated to a horizontal resolution of  $0.5^{\circ}$  latitude by  $0.5^{\circ}$  longitude using bilinear interpolation.

We calculated spatial correlation coefficients (SCCs), standard deviation, and centered root mean square errors (RMSEs) for the surface air temperature (SAT) and precipitation between the preindustrial experiments and the reanalysis data over East Asia. The results are presented as a Taylor diagram (Taylor, 2001; Figure 1). The models show a better skill in simulating temperature than precipitation, as indicated by the larger scatter of the precipitation statistics. The SCCs are greater than 0.85, and the RMSEs are less than





**Figure 2.** (a) Multimodel ensemble (MME) for summer mean surface air temperature (units: °C) differences between the mid-Pliocene and the preindustrial period. (b) MME of the atmosphere-ocean general circulation models for summer mean sea surface temperature (units: °C) differences between the mid-Pliocene and the preindustrial period. (c) MME for summer mean precipitation anomalies (units: mm/day, shading) between the mid-Pliocene and the preindustrial period, together with the preindustrial precipitation distribution (contours). Summer spans May-September for the Northern Hemisphere and November-March for the Southern Hemisphere. The shaded dots indicate areas where over 70% of the models agree with the direction of the change, calculated following the method of Koh and Brierley (2015).

0.50 for the SAT (Figure 1a), whereas for the precipitation, the SCCs range from 0.30 to 0.95, and the RMSEs of five models are much greater than 1 and those of the remaining 11 models are clustered between 0.5 and 1 (Figure 1b). As models with low RMSEs have a good simulation ability, 11 models (Figure 1b), with RMSEs of precipitation less than 1, were selected in this study to analyze the northern edge of the EASM.

#### 3. Results

#### 3.1. Temperature and Precipitation Anomalies During the Mid-Pliocene

The numerical simulations show that compared with the preindustrial period, the MME summer SAT in the mid-Pliocene was substantially warmer (approximately 4–5 °C) at northern high latitudes, while the low latitude SAT increased by 0–2 °C. The MME summer SAT of the mid-Pliocene was 2–4 °C warmer in the East Asian mainland (Figure 2a), while the SSTs of the South China Sea and the equatorial western Pacific were 1–2 °C higher in the mid-Pliocene than in the preindustrial period (Figure 2b). Evidently, there was an enhanced land-sea thermal contrast of 1–2 °C between the East Asian mainland and the equatorial western Pacific in the mid-Pliocene. With respect to the preindustrial period, summer MME precipitation increased in most areas of East Asia in the mid-Pliocene (Figure 2c). Specifically, there was a significant increase in precipitation in northern China (0.5–1.0 mm/day), whereas a slight increase or decrease in precipitation occurred in southern China.

#### 3.2. The Northern Edge of the EASM in the Mid-Pliocene

The northern edge of EASM was analyzed systematically, based on the previously mentioned definition. As shown in Figure 3, the northern edge of the EASM generally exhibits a northwestward shift during the mid-Pliocene compared with the preindustrial period, although the amplitudes of the migration differ among individual models. A large northwestward shift (~300–500 km) of the northern edge of the EASM was





Figure 3. The northern edge of the East Asian summer monsoon for the mid-Pliocene (red lines), the preindustrial (green lines), and the present day (1981–2010, black lines).

simulated by CAM4, FGOALS-g2, MIROC4m (AGCM and AOGCM), and NorESM for the mid-Pliocene, while a small northwestward shift (~50–100 km) of the northern edge of the EASM is evident in the other six models. The multimodel ensemble results for all the AGCMs and AOGCMs are similar, showing a ~150-km-northwestward migration of the northern edge of the EASM in the mid-Pliocene.

The present northern edge of the EASM (Figure 3), characterized on the basis of CMAP precipitation data (1981–2010), shows a northeast-southwest trend similar to that in the preindustrial period, but its location migrates significantly southeastward compared with the preindustrial period. This is related to the





**Figure 4.** Paleoclimatic records for the mid-Pliocene. Numbers refer to sites listed in Table 2. The solid line represents 500-mm isoline of annual precipitation, which is the present boundary between humid-subhumid and arid-semiarid areas, while the dotted line indicates the dry-humid boundary in the Pliocene.

southward displacement of the monsoon rainbelt observed during the last few decades due to the weakening of the EASM since the 1970s (Chase et al., 2003; Dai et al., 2012; Wang, 2001; Zhu et al., 2012). An additional cause is the summer "wet biases" over northern China in most of the coupled GCMs (Song & Zhou, 2014). These results generally demonstrate the good ability of the models to simulate the northern edge of the EASM; however, the ~150-km distance estimate for the EASM shift remains to be confirmed using high-resolution regional climate models.

#### 3.3. Data-Model Comparison

The paleoclimates and paleoenvironments of the Pliocene have been studied extensively using a variety of proxies, including paleontological indicators such as fauna, sporopollen assemblages, and fossil wood (Han et al., 1997; Li et al., 2004; Xie et al., 2012); geochemical proxies such as carbon and oxygen isotopes and trace elements (Ding & Yang, 2000; Ding et al., 2001; Jin & Li, 2003; Ma & Si, 2009); magnetic indices such as magnetic susceptibility (He et al., 2013; Nie et al., 2014); and sedimentological indicators such as grain size and soil formation (Ao et al., 2016; Ding et al., 1999, 2001; Qiang et al., 2001; Yang & Ding, 2004; Yang et al., 2018). To reduce uncertainties derived from multiple interpretations of various paleoclimatic proxies, palaeoclimatic records based on paleontological

indicators (sporopollen, plant macrofossils, ostracoda, and fauna), which are robust measures of palaeomonsoon intensity, were assembled. Paleontological data from 43 sites throughout China (Figure 4) were compiled to examine the spatial climatic pattern for the mid-Pliocene. The results (Table 2) show that 14 sites were dry and 29 sites were humid, with humid conditions in southeastern China and dry conditions in northwestern China during the mid-Pliocene—a pattern like that of the present. At present, the 500-mm isoline of annual precipitation marks the boundary between humid-subhumid and arid-semiarid areas (Figure 4; Sun & Wang, 2005). Clearly, the location of the wet-dry boundary, that is, the northern edge of the EASM, moved significantly northwestward during the mid-Pliocene relative to the present, especially over the region to the east of 110°E and to the west of 95°E.

The northwestward shift in the northern edge of the EASM captured by the models (Figure 3) is roughly consistent with that derived from the comparison of geological records and modern climatic data (Figure 4). However, there is a difference in the details between the simulations and reconstructions. The geological records show a greater magnitude of the EASM shift at the northeastern and southwestern ends of the edge, while the simulations display a roughly consistent northwestward shift of the edge. It follows that except for the north-south climatic contrast, an enhanced east-west contrast is distinct in the Pliocene geological records. This discrepancy may be related to (1) physical weaknesses in the models, such as the insufficient sensitivity to external perturbations, underestimation of internal variability, and failure to represent important feedbacks (Braconnot et al., 2012; Jiang et al., 2014), and (2) the proxy data compilation, which represents an amalgam of time snapshots in which the orbital configuration may have been different from that used in the PlioMIP model simulations. Thus, data-model comparisons confined to a very narrow time window of the mid-Pliocene are required in future studies (Haywood et al., 2013).

# 4. Mechanism for the Migration of the Northern Edge of the EASM

The modern EASM consists of tropical and subtropical monsoons (Ding & Chan, 2005). The northern edge of the EASM is substantially affected by the East Asian subtropical summer monsoon (Tang et al., 2008). Since the poleward flow along the western flank of the western Pacific subtropical high (WPSH) is a major component of the subtropical summer monsoon, the advance and retreat of the East Asian subtropical monsoon are closely related to the activity of the WPSH (Huang & Tang, 1987; Lu & Dong, 2001). Meteorological observations have shown that the northward shift and westward extension of the WPSH promote the northwestward displacement of the rainbelt and the precipitation in northern China increases accordingly (Huang et al., 2015; Tao & Wei, 2006).



#### Table 2

Localities and Data Used in the Mid-Pliocene Paleoclimatic Reconstruction

			Reconstructed			
No.	Site	Location	climate	Age (Ma)	Proxy data	References
1	Shijiawan	34.40°N, 109.60°E	Dry	3.0-2.7	Pollen and elephant fossil	Han et al. (1997)
2	Xifeng	35.88°N, 107.97°E	Dry	3.4-2.4	Pollen; mollusk	Wang et al. (2006); Wu et al. (2006)
3	Xifeng	35.70°N, 107.60°E	Dry	4.0-3.0	C <sub>4</sub> vegetation expansion	Jiang et al. (2002)
4	Yahu	37.80°N, 94.50°E	Dry	3.6-2.6	Pollen	Fang et al. (2008); Wu et al. (2011)
5	Guge	31.47°N, 79.74°E	Dry	3.2-2.9	Pollen	Yu et al. (2007)
6	Gonghe Basin	36.23°N, 100.68°E	Dry	3.15-3.05	Ostracods	Zhao (2013)
7	Sanju	37.18°N, 78.48°E	Dry	5.3-2.58	Pollen	Sun et al. (2008)
8	Dushanzi	44.30°N, 84.93°E	Dry	3.2-2.58	Pollen	Sun et al. (2007)
9	Tianzhu-Gansu	36.95°N, 103.28°E	Dry	Mid-Pliocene	Micromammalia	Zhen (1982)
10	Sikouzi	36.26°N, 105.98°E	Dry	3.3-3.0	Pollen	Jiang and Ding (2008)
11	Jiuxi Basin	39.78°N, 97.53°E	Dry	3.6-3.3	Pollen	Ma, Fang, et al. (2005)
12	Qaidam Basin	37.80°N, 94.80°E	Dry	3.3-3.0	Pollen	Wu et al. (2011)
13	Dongwan	34.97°N, 105.78°E	Dry	4.55-3.5	mollusk	Li et al. (2014); Liu et al. (2011)
14	Renjiagou	34.98°N, 107.56°E	Dry	3.5-3.4	Mammalia	Zhang and Gong (2003)
15	Zanda Basin	31.67°N, 79.75°E	Wet	3.5-2.9	Gastropod and Pollen	Zhu et al. (2007)
16	Zanda Basin	31.00°N, 80.00°E	Wet	4–3.1	Mammalian	Wang, Li, et al. (2013); Wang, Xu, et al. (2013)
17	Qaidam Basin	38.38°N, 91.75°E	Wet	3.1-2.6	Pollen	Cai et al. (2012)
18	Lingtai Leijiahe	35.07°N, 107.73°E	Wet	5.8-3.4	Pollen	Wu (2001)
19	Chaona	35.12°N, 107.20°E	Wet	3-2.6	Pollen	Ma, Wu, et al. (2005); Nie et al. (2014); Wu et al. (2007)
20	Baode	39.02°N, 111.16°E	Wet	3.05-2.8	Pollen	Li et al. (2011)
21	Yushe Basin	36.97°N, 112.83°E	Wet	3.5-2.3	Pollen	Liu et al. (2002); Shi et al. (1993)
22	Zhangcun	37.80°N, 114.20°E	Wet	4.4-2.3	Pollen	Li et al. (2004)
23	Taigu	38.00°N, 113.60°E	Wet	4.0-3.0	Pollen	Li et al. (2004)
24	Hujiachi	37.50°N, 115.50°E	Wet	3.5-3.11	Pollen	Bi et al. (2012)
25	Tianzhu-Beijing	40.10°N, 116.54°E	Wet	3.58-2.55	Pollen	Yao et al. (2007)
26	Tangshan	39.54°N, 118.17°E	Wet	3.58-3	Pollen	Hu et al. (2014)
27	Zibo	36.81°N, 118.06°E	Wet	3-2.9	Pollen	Tan et al. (2000)
28	Qianan	44.78°N, 123.73°E	Wet	3.3-2.45	Pollen	Jia et al. (1989); Xia and Wang (1987)
29	Hujiacun	29.60°N, 120.73°E	Wet	3.5-3.0	Alseodaphne	Hu et al. (2007)
30	Huaibei Plain	33.33°N, 117.33°E	Wet	4.5-2.5	Pollen	Yu and Huang (1993)
31	Tuantian	24.68°N, 98.62°E	Wet	3.3–2.3	Carpinus Miofangiana; Megaflora	Dai et al. (2009); Wu et al. (2009); Xie et al. (2012)
32	Wanbaoshilin	25.86°N, 101.81°E	Wet	3.4-2.5	Megaflora	Cheng et al. (2005)
33	Hutaotantulin	25.84°N, 101.76°E	Wet	3.4-2.5	Megaflora	Cheng et al. (2005)
34	Yuanmou Basin	25.50°N, 102.00°E	Wet	3.4-2.5	Megaflora; Pollen	Liu et al. (2002); Yao et al. (2012)
35	Weihe	34.52°N, 109.50°E	Wet	3.04-2.91	Pollen	Tong et al. (1989)
36	Huanghua	38.40°N, 117.33°E	Wet	3.2-3.11	Pollen	Fan et al. (2009)
37	Tianjin	39.07°N, 117.63°E	Wet	3.61-2.8	Pollen	Yang, Qin, et al. (2015)
38	Daodi	40.15°N, 114.66°E	Wet	3.7-2.6	Mammalia	Li et al. (2008)
39	Nihewan 1	40.22°N, 114.64°E	Wet	2.92-2.82	Pollen	Ding et al. (2018)
40	Nihewan 2	40.21°N, 114.64°E	Wet	3.3-3.06	Pollen	Li (2018)
41	Tianshui	34.39°N, 105.71°E	Wet	3.2-2.6	Pollen	Liu (2016)
42	Changjiang Delta	31.34°N, 121.84°E	Wet	3.3-2.7	Pollen	Xie (2017)
43	Gaotege	43.50°N, 115.44°E	Wet	4.0-3.6	Rodentia	Li et al. (2003); Wang (2013)

The MME summer wind anomaly field at 850 hPa between the mid-Pliocene and the preindustrial period was calculated (Figures 5a and 5b). Evidently, there is an anomalous anticyclonic circulation across the region from 105°E to the western Pacific, indicating a significantly enhanced WPSH in the mid-Pliocene. Moreover, the anomalous southeasterly wind associated with the WPSH extends northward up to 30°N, implying an intensified southeasterly wind in this area. Obviously, the EASM was intensified during the mid-Pliocene, which well explains the northwestward migration of its northern edge.

The position of the WPSH is conventionally measured by the geopotential height at 500 hPa (Ding, 1994; Zhou & Li, 2002). We adopted the 5,843-gpm contour line of the 500-hPa geopotential height to describe the position of the WPSH (Gong & Ho, 2002; Nitta & Hu, 1996; Figure 5c) and found a remarkable





**Figure 5.** (a) Summer wind field (m/s) at 850 hPa for the preindustrial period. (b) Summer wind field (m/s) anomaly between the mid-Pliocene and the preindustrial. The shaded dots indicate areas where over 70% of the models agree with the direction of the change, calculated following the method of Koh and Brierley (2015). Note the good agreement across the ensemble in the western flank of the western Pacific subtropical high. (c) The 5,843-gpm contour line of 500-hPa geopotential height for the preindustrial period (green) and the mid-Pliocene (red), together with the multimodel ensemble for summer mean precipitation anomalies (units: mm/day, shading) between the mid-Pliocene and the preindustrial period.

difference in the position and extent of the WPSH between the mid-Pliocene and the preindustrial period. Compared with the preindustrial period, the WPSH in the mid-Pliocene extended significantly westward, which favored the penetration of the southeasterly wind from the western flank of the WPSH into the interior of the Asian continent. Therefore, the westward extension of the WPSH, together with the strengthening of its intensity, promoted the northwestward advance of the EASM, leading to a deeper penetration of the rainbelt into northern China during the Pliocene warmth. This is inconsistent with the prediction of Held and Soden (2006) that Earth's dry regions will become drier and its wet regions wetter, with global warming. However, a recent study (Allan, 2014) has demonstrated that the pattern suggested by Held and Soden (2006) would be invalid if global warming induced shifts in atmospheric circulation patterns.

Our results suggest a mechanism for the EASM variations in the context of the Pliocene warmth: That is, the enhanced land-sea thermal contrast between the East Asian mainland and the equatorial western Pacific resulted in an increased pressure difference between the land and sea (Chen et al., 2001), and hence a west-ward extension and strengthening of the WPSH, which in turn led to a northwestward shift in the north edge of the EASM. As the Tibetan Plateau topography generally decreased in the mid-Pliocene compared to the present day (Dowsett et al., 2010; Zhang et al., 2013), a stronger EASM intensity in future global warming scenarios, compared to the mid-Pliocene, is expected due to the influence of the plateau on orographically related thermal forcing of the EASM (Wu et al., 2012). Therefore, we propose that if global warming continues, the WPSH will extend westward, causing a northwestward shift in the EASM rainbelt and the resulting mitigation of droughts in northern China. It should be noted that all simulations used in this study were undertaken with global climate models and high-resolution regional climate models are urgently needed to investigate the northern edge of the EASM in greater detail.

# 5. Conclusions

The multimodel ensemble results of the PlioMIP models show that the summer SAT of the mid-Pliocene increased by approximately 2–4 °C in the East Asian mainland and by approximately 1 °C in the equatorial western Pacific, which significantly enhanced the east-west land-sea thermal contrast. The northern edge of the EASM featured a northwestward migration of ~150 km in the mid-Pliocene relative to the preindustrial period, which promoted the northwestward displacement of the rainbelt and an increase of approximately 0.5–1 mm/day of summer mean precipitation in northern China.



A data-model comparison shows that the northwestward shift of the northern edge of the EASM simulated by the models is consistent with that derived from a comparison of geological records and modern climatic data. However, the geological records show a greater magnitude of the EASM shift at the northeastern and southwestern ends of the edge, compared to the simulations. This indicates that except for the north-south climatic contrast, an enhanced east-west contrast is evident in Pliocene geological records, which needs to be addressed in future modeling studies.

The simulations show that compared with the preindustrial period, the position of the WPSH in the mid-Pliocene was extended substantially westward, and its intensity increased, favoring the inland penetration of the southeasterly winds from the western flank of the WPSH. This induced the northwestward shift of the mid-Pliocene northern edge of the EASM. Therefore, we suggest that future global warming may lead to an intensification and westward extension of the WPSH, thereby intensifying the EASM and mitigating droughts in northern China.

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