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Paleoclimate Modeling in China: A Review

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ABSTRACT

This paper provides a review of paleoclimate modeling activities in China. Rather than attempt to cover all topics, we have chosen a few climatic intervals and events judged to be particularly informative to the international community. In historical climate simulations, changes in solar radiation and volcanic activity explain most parts of reconstructions over the last millennium prior to the industrial era, while atmospheric greenhouse gas concentrations play the most important role in the 20th century warming over China. There is a considerable model–data mismatch in the annual and boreal winter temperature change over China during the mid-Holocene [6000 years before present (ka BP)], while coupled models with an interactive ocean generally perform better than atmospheric models. For the Last Glacial Maximum (21 ka BP), climate models successfully reproduce the surface cooling trend over China but fail to reproduce its magnitude, with a better performance for coupled models. At that time, reconstructed vegetation and western Pacific sea surface temperatures could have significantly affected the East Asian climate, and environmental conditions on the Qinghai–Tibetan Plateau were most likely very different to the present day. During the late Marine Isotope Stage 3 (30–40 ka BP), orbital forcing and Northern Hemisphere glaciation, as well as vegetation change in China, were likely responsible for East Asian climate change. On the tectonic scale, the Qinghai–Tibetan Plateau uplift, the Tethys Sea retreat, and the South China Sea expansion played important roles in the formation of the East Asian monsoon-dominant environment pattern during the late Cenozoic.

Key words: paleoclimate modeling, China, millennium, orbital scale, tectonic scale

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1. Introduction

Physically-based climate models have been widely applied in the geosciences in recent decades. One of the hottest topics by far is the projection of anthropogenic climate change on the basis of a series of scenarios of atmospheric greenhouse gas and aerosol concentrations. However, high levels of uncertainty still exist in current climate models. In an attempt to objectively evaluate the efficacy of climate models under various boundary conditions, and to scientifically understand the mechanism of climate change over a

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wide range of timescales, more and more attention has been paid worldwide to paleoclimate modeling since the 1990s (Joussaume and Taylor, 1995). By comparing simulations with reconstructions, our knowledge on past climate change has been greatly advanced in many respects (Cane et al., 2006; Jansen et al., 2007).

As an interdisciplinary subject, studies on past climate change consist of both reconstructions and simulations. Since the pioneering research of Chu (1973), a great deal of climate reconstruction has been carried out in China through the use of historical documents, tree rings, ice cores, stalagmites, peat, pollen, fluvial and marine sediments, lacustrine sediments, loesses, and paleosols. The regional climate of China has been found to have undergone large changes on varying timescales. These proxy data also form a solid foundation upon which paleoclimate modeling can be built, allowing qualitative and/or quantitative model–data comparisons to be made.

A variety of climatic states and events in Earth's history have been recorded. Paleoclimate modelers tend mainly to be interested in abnormal climatic intervals, which feature significantly different climates from the present day, and have abundant proxy data to be used alongside. For instance, the mid-Holocene is an ideal period for evaluating the response of climate models to different seasonal distributions of insolation due to changes in the Earth's orbital parameters, and the Last Glacial Maximum (LGM) is equally suitable for evaluating the ability of climate models to reproduce extremely cold climates and for understanding how massive ice sheets and lower atmospheric CO_2 concentrations affect the climate system (Jansen et al., 2007). The last millennium bridges the periods containing proxy data as well as modern instrumental observations and thus provides a unique opportunity for seeking the nature and cause of climate change on decadal to centennial scales, and for distinguishing the effect of anthropogenic activity from natural climate variability, which is of course an issue of great concern for both the social and scientific communities. Additionally, simulations of the climate of the mid-Pliocene, *ca.* 3 million years before present (Ma BP), known as the most recent geological era when global climate was significantly warmer than at present, will improve our knowledge of the operation of a warmer-than-present climate regime, which is likely to be very helpful in evaluating man-made global warming in the future (Jansen et al., 2007).

China is one of the most densely populated areas on Earth. Its natural environments, which are influenced greatly by geographic location, topography, and geomorphology, are susceptible and vulnerable to climate change. Statistically, annual meteorological disasters during the 1990s accounted for as much as 3%–6% of the Gross Domestic Product of China, with larger percentages in years that featured significant climate anomalies (Huang et al., 2003). Accordingly, more and more attention is being paid to investigate past, present, and future climate changes in China. It should be noted, however, that although numerous paleoclimate simulations have been reported worldwide in the scientific literature, few have focused on past climate change in China and adjacent regions, as compared to the North Atlantic, Europe, North America, etc.

Based on reconstructions, considerable effort has been made by Chinese scientists to simulate past climate change and events in East Asia and across the globe for more than two decades. This began with Wang and Zeng (1992a, 1992b), with their simulations of the climate of the LGM and that of 9000 years before present (ka BP). The motivation behind this paper is to present a review of those scientific activities, with the aim being to facilitate forthcoming paleoclimate simulations, particularly for the East Asian monsoon region. In section 2 we discuss historical climate modeling. Section 3 reports on the progress made in the area of mid-Holocene climate modeling and abrupt climate change over China at 4 ka BP. Simulations of the LGM and the late Marine Isotope Stage 3 (MIS3) are reviewed in sections 4 and 5, respectively. Section 6 is devoted to pre-Quaternary climate modeling; specifically, the mid-Pliocene, the impact of tectonic changes on the late Cenozoic climate, the climatic consequences of the Qinghai–Tibetan Plateau (QTP) uplift, and the East Asian climate transition during the Cenozoic. Finally, some conclusions and perspective are presented in section 7.

2. Historical climate modeling

2.1. *Reconstructed historical climate in China*

The last millennium is a key period for linking proxy records and instrumental observations, during which time the Earth's environment and ecology have become increasingly changeable due to the increasing influence of human activity. It provides us with a unique opportunity to evaluate the variability induced by anthropogenic and natural factors, which is particularly important for understanding global warming over recent and coming decades.

Based on historical documents, stalagmites, tree rings, lacustrine sediments, ice cores, and so on, effort has been made to reconstruct historical climate change over China (e.g., Chu, 1973; Zhang, 1980; Shao et al., 2005; Gou et al., 2008; Zhang et al., 2008; Tan et al., 2009). For the last two millennia, Yang et al. (2002) used multiple proxy records to establish three China-wide temperature series. Five temperature phases were identified: a warm stage during 0–240; a cold interval during 240–800; a return to a warm stage during 800–1400; a cold interval during 1400–1920; and the present warm stage from 1920. For the last millennium, Wang et al. (2007) used several kinds of records to reconstruct regionally averaged temperature series for 10 regions of China. After that, temperature series for the whole country were obtained by averaging the regional series in terms of the size of the regions. On the decadal scale, temperature change in eastern China was different from that of western China. In the first 400 years, temperature was above normal in the east but near or lower than the normal in the west. Temperature increased by almost 1 K in the west, but only ~ 0.5 K in the east from the 17th to the 20th century. Warming in the 20th century was strongest in western China. Both the Medieval Warm Period (MWP) and Little Ice Age (LIA) occurred in the east, but probably not in the west, although the 17th century was also cold in the west. In addition, the reconstructed thermal contrast in East Asia was strongest (weakest) in the MWP (early LIA), with more (less) precipitation in North China and less (more) precipitation in southern China (Zhou et al., 2011b).

2.2. *Last millennium climate modeling in China*

There are uncertainties in reconstructions due to the sparse coverage of proxy data and their translation into climate. More importantly, proxy records themselves cannot explain the mechanisms underpinning historical climate change. There are a variety of issues calling for investigation into climate change over the last millennium from the perspective of climate modeling. For example, what was the climate during the MWP, LIA, and present warm period? Which period had the more significant warming: the MWP or the 20th century? What were the mechanisms responsible for historical climate change over China on decadal to centennial scales?

2.2.1. *The last millennium climate forcing*

For the last millennium, solar variation and volcanic activity are likely to be leading reasons for climate change before the start of the industrial era, while anthropogenic greenhouse gases and aerosols become important factors for climate change thereafter (Jansen et al., 2007). Solar variation is usually estimated by a combination of observed sunspot numbers and cosmogenic isotope production as recorded in ice cores and tree rings (e.g., Crowley, 2000). Volcanic histories are based on analyses of polar ice cores containing minor dating uncertainty and obvious geographical bias. Meanwhile, there are some differences in the way that models implement records of volcanic activity (Jansen et al., 2007). For atmospheric concentrations of greenhouse gases, both reconstructed and simulated series have been used in simulations (e.g., Crowley, 2000; Joos et al., 2004). Besides those factors, orbital insolation is computed with the algorithm of Berger (1978). The effect of land-use and land-cover change and atmospheric aerosol concentrations has also been included in several simulations, although their spatiotemporal evolutions are highly uncertain. Overall, these two anthropogenic factors cause a negative forcing, which tends to offset the effect of greenhouse gas warming (Hansen et al., 1998).

2.2.2. *Time-slice simulations for the MWP, LIA, and 20th century*

Using solar radiation, volcanic aerosols, and reconstructed vegetation, Liu et al. (2004) performed a set of experiments for the LIA using an atmospheric general circulation model (AGCM). In response to decreased solar radiation, annual temperature reduced in China. Temperature decrease was more obvious in summer (June to August throughout this paper) than in winter (December to February throughout this paper), which was due to the larger changes in net solar radiation at the top of the atmosphere in summer than in winter. Volcanic aerosols reduced winter temperature, but to less an extent than solar radiation. The synergistic effect of the reduced solar radiation and increased volcanic aerosols had a superposed strengthening impact on temperature decrease in large regions. An increase in vegetation cover gave rise to temperature increase, and vice versa. Meanwhile, reduced solar radiation increased summer precipitation in East Asia, while increased volcanic aerosols had little or no effect on annual precipitation in most parts of Eurasia. The combined effect of solar radiation and volcanic aerosols led to an increase in summer precipitation averaged over eastern China (20°–40°N, 105°–120°E), but a decrease in South Asia. In addition, there was a weak anti-correlation between the Indian monsoon and East Asian subtropical monsoon, because when the Indian monsoon trough enhanced, the western North Pacific Subtropical High extended westward, reducing the rainfall along the East Asian subtropical front. Precipitation in eastern China increased (decreased) when vegetation cover increased (decreased). Further study is required to establish the reason behind this feature.

Later, six sets of time-slice and equilibrium simulations for the MWP during 1100–1200, the LIA during 1650–1750, and the 20th century were conducted with the Flexible Global Ocean–Atmosphere–Land System Model (FGOALS) (Zhou et al., 2008; Zhang et al., 2009; Man et al., 2010; Zhou et al., 2011a; Zhou et al., 2011b). The effect of solar radiation and volcanic activity was found to largely contribute to the warming (cooling) in the MWP (LIA), while an increase in atmospheric greenhouse gas concentrations played more important roles in the 20th century warming, which was consistent with the results of phase 3 of the Coupled Model Intercomparison Project (Zhou and Yu, 2006). The MWP warming was evident on a global scale, except for the mid-latitude North Pacific, and was weaker in magnitude than that in the 20th century. The LIA cooling was also evident on a global scale, with a larger magnitude in the Northern Hemisphere (NH) than in the Southern Hemisphere (SH) and in the high latitudes than in the lower latitudes. Global model–data comparisons indicated that FGOALS's performance in simulating the temperature change during the warm periods was better than during the LIA, while model–data consistency in lower latitudes was better than in high latitudes. A comparison of the simulated LIA temperature with proxy data in eastern China showed a high level of consistency. The interannual variability mode of the East Asian summer monsoon (EASM) rainfall during the MWP, LIA and 20th century displayed a consistent pattern. On the centennial scale, the external mode of the EASM variability driven by effective solar radiation was determined by the change of large-scale land–sea thermal contrast. The EASM was strongest in the MWP but weakest in the LIA. When the EASM was weaker, the monsoon rain belt in eastern China was generally located more southward, with less precipitation in North China and more precipitation in the Yangtze River valleys; namely, a southern flood/northern drought pattern. Globally, there was more precipitation in the MWP and 20th century but less in the LIA. The results corresponded well to the synchronous evolution of global temperature, which resembled simulations with the ECHO-G (ECHAM4 and the global Hamburg Ocean Primitive Equation coupled ocean–atmosphere model) (Liu et al., 2009a). However, the EASM and precipitation did not vary synchronously with the trend of global temperature. During the last 150 years, for example, although the temperature around the world and in China increased, the EASM and precipitation possessed no detectable trend.

2.2.3. *Transient simulations for the last millennium*

The Earth system model of intermediate complexity, the McGill Paleoclimate Model-2, was used to simulate climate change during 1000–1800 by Yin et al. (2007). The joint effect of solar variability and volcanic eruptions was found to form the basic pattern of temperature evolution and explain the major characteristics of climate change at the global and northern hemispheric scales, where solar variability was responsible for the long-term trend, with volcanism possibly strengthening or weakening this trend. Based on the same model, Shi et al. (2007) conducted further experiments to evaluate the effect of anthropogenic land-cover change. The biogeophysical effect of historical land-cover change decreased global annual temperature by 0.09–0.16 K (0.14–0.22 K in the NH during the last 300 years), indicating the importance of this factor in climate over the last millennium.

Control and transient simulations for the last millennium using the ECHO-G atmosphere–ocean general circulation model (AOGCM) have also been used to examine regional climate in China. Liu et al. (2005) compared these simulations with reconstructed winter half-year temperature in central eastern China (Ge et al., 2003). The correlation coefficient between the simulated and reconstructed time series was 0.37, which was statistically significant at the 97.5% confidence level. The MWP during 1000–1300, the LIA during 1300–1850, and the modern warm period after 1900 all appeared in both the simulated and reconstructed temperature. The simulations for the LIA and the 20th century were in good agreement with reconstructions and/or observations. In particular, both the simulated and reconstructed temperature reached their minima in the Maunder sunspot minimum during 1670–1710. For the MWP, however, significant discrepancies existed between the simulation and reconstruction, which might partly reflect the degrading quality of reconstructions (Ge et al., 2003) and the model's deficiency in initialization. Overall, variations in solar radiation and volcanic activity were found to be the main factors for temperature change over China before the 20th century, while variations in atmospheric greenhouse gas concentrations played the most important role in the 20th century warming, which was in line with the aforementioned time-slice simulations.

Monsoon precipitation affects about two thirds of the world's population. Its response to external and anthropogenic forcings during the last millennium has also been examined based on ECHO-G simulations (Liu et al., 2009a). The monsoon precipitation domain over the globe was defined by the regions in which the annual range of precipitation exceeds 2 mm d^{-1} and the local summer precipitation exceeds 55% of annual rainfall (Wang and Ding, 2008). The strength of global monsoon precipitation was found to undergo a significant variation with a prominent quasi-bicentennial oscillation. It was weak in the LIA, but strong in the MWP. Before the industrial period, effective solar radiation variations reinforced the thermal contrasts both between the ocean and land and between the NH and SH, resulting in a millennium-scale variation and quasi-bicentennial oscillation in the global monsoon index. The prominent upward trend in global monsoon precipitation in the last century and the remarkable strengthening of the global monsoon during 1961–90 appeared unprecedented and were due possibly in part to the increase of atmospheric greenhouse gas concentrations. The global monsoon in the last 30 years had a different spatial pattern from that in the MWP, suggesting that greenhouse gas and solar/volcanic forcing might have different impacts on global monsoon precipitation. Global monsoon strength was closely related to the temperature difference between the NH and SH, and on the centennial scale it responded more directly to the effective solar forcing than the concurrent forced response in global temperature.

Based on the ECHO-G simulations, it was also found that the centennial–millennial variation of the EASM precipitation was essentially a forced response to the external radiative forcing over the past millennium (Liu et al., 2011). The strength of the response depended on latitude, and the spatial structure of the centennial–millennial variation differed from the interannual variability that arose primarily from the internal feedback of the climate system. On the millennial scale, extratropical and subtropical precipitation was generally strong (weak) in the MWP (LIA). Tropical rainfall was insensitive to the effective solar radiation forcing but responded significantly to modern anthropogenic radiative forcing. On the centennial scale, the variation of extratropical and subtropical rainfall also tended to closely follow the effective solar radiation forcing. The forced response featured in-phase rainfall variability between the extratropics and subtropics, which was in contrast to the anti-correlation on the interannual scale. As such, the proxy data in extratropical East Asia could more sensitively reflect EASM rainfall, and the Mei-yu and northern China rainfall provided a consistent measure for EASM strength on the millennial scale. Further simulations indicated that EASM circulation during the MWP was stronger than during the LIA as a result of land–sea thermal contrast change caused by the effective radiative forcing (Man et al., 2012; Man and Zhou, 2014). There was a coherent cooling over East Asian continent and the tropical ocean after large volcanic eruptions, and stronger cooling over the mid-high latitudes of the East Asian continent than over the tropical ocean led to a reduced land–sea thermal contrast and hence a weak EASM circulation (Man et al., 2014).

In addition to analysis of available simulations, Peng et al. (2009) used the Community Climate System Model (CCSM) version 2.0.1 AOGCM to simulate climate change over the last millennium. The simulated temperature across the whole of China and in eastern China correlated to some extent with reconstructions, while simulated precipitation in eastern China and in the middle and lower reaches of the Yangtze River valleys displayed some similarities with reconstructions for certain periods of time. Both simulations and reconstructions indicated that the 20th century warming was anomalous in a long-term context. The wet and dry conditions appeared alternately in eastern China in the MWP. Dry conditions dominated in the LIA, whereas wet conditions prevailed after 1890. The correlation between the simulated and reconstructed precipitation was better in the middle and lower reaches of the Yangtze River valleys than in eastern China, especially before 1850. Regional climate differences were present in eastern China in the last millennium, and there were no fixed modes of climate change, such as warm–wet or cold–dry. Temperature and precipitation in eastern China were controlled mainly by the changes in effective solar radiation and volcanic activity, while atmospheric greenhouse gas concentrations played a leading role in the rapid warming of the past 150 years. Shen et al. (2009) used these simulations to further examine summer precipitation variability in eastern China. Model–data comparisons suggested that the centennial oscillation might be linked to the fluctuation of solar forcing, and the decadal oscillation could be associated with internal variability of the climate system. The increased frequency of the southern flood/northern drought pattern in eastern China over the last two decades was unusual over the past five centuries.

FGOALS reproduced the MWP, LIA, and 20th century warming reasonably, with enhanced warming over northern high-latitude continents (Man and Zhou, 2014). Model–data consistency was lower on regional scales than on hemispheric scales. Different from significant global signals in the 20th century, climate changes during the natural-forcing-dominant periods were mainly manifested in the NH; and total external forcings explained about half of the climate variance and significantly impacted the evolution of atmospheric oscillations during the last millennium, especially at decadal scales (Man and Zhou, 2011; Zhang et al., 2013a). FGOALS's sensitivity to natural forcings is generally weak, leading to a weak MWP (Guo and Zhou, 2013). The model sensitivity in the industrial era is higher than that of the pre-industrial period. Both the weaker negative net cloud feedback and stronger water vapor feedback in the industrial era than in the pre-industrial period favor higher model sensitivity and thus a reasonable simulation of the 20th century warming.

2.3. *Perspective*

The aforementioned simulations generally showed that solar radiation and volcanic activity accounted for large parts of the MWP and LIA climate, while atmospheric greenhouse gas concentrations played the most important role in the 20th century warming both in China and across the globe. The warming in the MWP was likely weaker than that in the 20th century over China. The effect of land-cover change could also be important for historical climate change, particularly in the last 300 years. Since both similarities and differences have been noticeable when simulations were compared to reconstructions in China in the context of the last millennium (e.g., Liu et al., 2005; Peng et al., 2009; Man et al., 2012; Man and Zhou, 2014), in future work it is necessary to use climate models to perform transient simulations and evaluate the effect of not only solar radiation, volcanic eruptions, and atmospheric greenhouse gas concentrations, but also anthropogenic aerosols and land-use and land-cover change. Uncertainties of last millennial climate simulation are resulted from both the specified external forcing data and the model sensitivity to natural/anthropogenic forcings. The millennial climate simulation driven by different external forcing data including effective solar radiation and volcanic aerosol should be compared. Multi-model inter-comparison should also be performed, and the sensitivities of climate models to the natural/anthropogenic forcing should be studied. Where regional climate is concerned, the horizontal resolution of global climate models is too coarse to perform a transparent model–data comparison. Regional climate models should be emphasized in that area, particularly for historical climate events such as the MWP and LIA.

3. Mid-Holocene climate modeling and abrupt climate change in China at 4 ka BP

3.1. *Mid-Holocene climate modeling in China*

3.1.1. *Reconstructed mid-Holocene climate in China*

The mid-Holocene was a typical interglacial period at *ca.* 6 ka BP, and many efforts have been devoted worldwide to investigating the response of climate models to the different seasonal distributions of incoming insolation for that time (Jansen et al., 2007). Based on records from pollen, fossil remains of plants and animals, paleosols, lacustrine sediments, ice cores, stalagmites, and Neolithic archaeological evidence, the mid-Holocene megathermal was inferred to occur at 8.5–3.0 ka BP, with stable warmer and wetter conditions during *ca.* 7.2–6.0 ka BP over China (Shi et al., 1993; Jiang et al., 2012, 2013b). For that period, the deviation of annual temperature from the present day was estimated roughly as 1 K in South China, 2 K in the Yangtze River valleys, 3 K in North China and Northeast China, and 4–5 K on the southern QTP. Moreover, winter warming was stronger than annual warming; summer monsoon intensified; winter monsoon weakened in East Asia; vegetation zones shifted northwestward; and higher levels of inland lakes occurred in Inner Mongolia, Xinjiang, Qinghai, and Tibet, implying wetter climates (e.g., Shi et al., 1993; Qin and Yu, 1998; Yu et al., 2003a). These proxy data provide a benchmark for mid-Holocene climate modeling and an opportunity for examining the dynamic mechanisms underpinning the changes.

3.1.2. *Mid-Holocene boundary conditions*

Under the framework of the Paleoclimate Modeling Intercomparison Project (PMIP; Joussaume and Taylor, 1995), boundary conditions for AGCMs are composed of changes in the Earth's orbital parameters and atmospheric CO_2 concentrations. The former led to an enhanced (reduced) seasonal cycle of insolation in the NH (SH), by about 5% (Berger, 1978). The latter were set to 280 ppmv from the present value of 345 ppmv. For AGCMs coupled with a slab ocean model in PMIP Phase 1 (PMIP1), sea surface temperatures (SSTs) were computed. Within PMIP Phase 2 (PMIP2) and Phase 3 (PMIP3), apart from the Earth's orbital parameters being the same as in PMIP1, atmospheric CO_2 concentrations were held at 280 ppmv both for the pre-industrial period and mid-Holocene. Atmospheric CH_4 concentrations were set to 650 ppbv for the mid-Holocene and 760 ppbv for the pre-industrial period. SSTs and sea ice extent were computed in PMIP2/3. Other aspects of PMIP2/3 boundary conditions were kept the same as in PMIP1. Besides the above boundary conditions recommended by PMIP, reconstructed vegetation (e.g., Shi et al., 1993; Yu et al., 2000), rather than present day vegetation, has been used in several simulations in order to evaluate the effect of vegetation on mid-Holocene climate in China.

3.1.3. *Mid-Holocene climate modeling*

Since the work of Wang and Zeng (1992a), considerable effort has been made to simulate the mid-Holocene climate in China. Wang (2000) indicated that, during mid-Holocene summers, temperatures rose by 1–4 K in much of the northern continents, the African and Asian monsoons intensified significantly, and precipitation increased by 10%–20% over China. When changes in the mid-Holocene Earth's orbital parameters alone were considered, both summer warming and winter cooling were significant in East Asia (Chen et al., 2002). In this region, the mid-Holocene summer temperature was ~ 2 K warmer in areas south of 40°N, whereas winter temperature was ~ 2 K colder than at present. When viewed from multiple climate models, 36 PMIP1/2 models reproduced colder-than-baseline annual temperature, with an average cooling of 0.4 K, over China, while seasonal temperature changes closely followed changes in incoming solar radiation at the top of the atmosphere over the country, with a summer warming but a winter and spring cooling (Jiang et al., 2012). Thirty-six PMIP1/2/3 models indicated that mid-Holocene annual precipitation, evaporation, and net precipitation were 3%, 1%, and 7% more than the baseline period, respectively; and seasonally, all three variables decreased in boreal winter and spring but increased in boreal summer and autumn on the national scale (Jiang et al., 2013b). For CCSM3 AOGCM simulations, both the East Asian winter and summer monsoons strengthened in response to an increased land–sea thermal contrast, while the changes of boreal spring and summer tropospheric thermal contrasts between Asia and the North Pacific played crucial roles in atmospheric circulation and precipitation changes over the Asian–Pacific region during the mid-Holocene (Zhou and Zhao, 2009, 2010, 2013). The mid-Holocene EASM strengthened by 32% across 28 PMIP1/2/3 models with a demonstrable ability to simulate the modern EASM climatology (Jiang et al., 2013a).

Regional climate models with high horizontal resolutions have also been used to examine the mid-Holocene East Asian climate (e.g., Zheng et al., 2004, 2007; Liu et al., 2009b). For example, Zheng et al. (2007) investigated mid-Holocene changes in hydrological processes in eastern and western China. It was found that wetter and warmer climates dominated on the QTP during that period. The increased amount of water vapor arriving on the plateau came mostly from its western boundary, and the increase in runoff stemmed mainly from increased precipitation. The mid-Holocene increase in precipitation and runoff in eastern China was closely related to strengthened Asian summer monsoon, which led to increased vapor coming into the area through its southern boundary.

In response to warmer and wetter climates, the mid-Holocene vegetation conditions differed largely from the present day in China. In general, tropical broadleaf-evergreen trees extended northward and a large area was covered by forests in eastern China, while forests on the QTP extended towards higher altitudes (Shi et al., 1993; Yu et al., 2000). Wang (1999a) revealed that changes in vegetation and associated soil characteristics further enhanced monsoon precipitation in China during mid-Holocene summers, as they decreased surface albedo and, in turn, increased land surface temperature, which reinforced monsoon via an increased land–sea thermal contrast. With the same mechanism, reconstructed vegetation was found to lead to a warming of 1.0–2.0 K, 0.5–1.0 K, and 0.5–1.5 K for the mid-Holocene summer, winter, and annual mean temperatures in East Asia, respectively (Chen et al., 2002). Accordingly, the thermal contrast between the East Asian continent and western North Pacific enlarged and caused a stronger EASM as described by Wang (1999a). The effect of vegetation in the Asian and African monsoon areas was also corroborated by Wang (2002), in which a coupled atmosphere–vegetation model was used to simulate the mid-Holocene climate. By contrast, averaged across six pairs of PMIP2 coupled models with and without a dynamic vegetation model, interactive vegetation was found to have little effect on mid-Holocene annual and seasonal temperatures in China (Jiang et al., 2012), which was also supported by recent simulations (Tian and Jiang, 2013). Note that their spread in vegetation-induced temperature changes between each of the six pairs of models implied a level of uncertainty in the mid-Holocene vegetation effect over the country. Recently, interactive vegetation was found to affect the interannual and interdecadal variability of the Asian summer monsoon in the mid-Holocene and in the present day (Li et al., 2009). In strong interannual or interdecadal South Asian summer monsoon years, dynamic vegetation tended to keep the intensity of westerly wind over South Asia in the lower troposphere for both periods. However, in strong interannual or interdecadal western North Pacific monsoon years, dynamic vegetation tended to reduce the westerly wind and the south–north cross-equator transport over the tropical western Pacific in the lower troposphere for both periods. This suggested that the impact of dynamic vegetation was more obvious on the western North Pacific monsoon than on the South Asian monsoon. In other words, it implies the impact of dynamic vegetation on the intensity of interannual circulations is region-dependent.

Since the effect of ocean dynamics was neglected in PMIP1, an asynchronously coupled AGCM and an oceanic general circulation model (OGCM) were used to quantify the role of orbital forcing and the ocean in forming the mid-Holocene East Asian climate (Wei and Wang, 2004). With reference to the simulation by the AGCM alone, more precipitation and stronger monsoon were reproduced in East Asia during summer, while winter temperatures rose over China due to the large thermal inertia of the ocean. It was revealed that solar radiation changes increased the convergence of atmosphere toward the land, and SST changes transported more moisture to the sea surface atmosphere during mid-Holocene summers. Their synergistic effect on East Asian precipitation was much stronger than the sum of their respective effects. Later, FGOALS simulations reproduced an enhancement of the Asian monsoon, which resulted from an increased land–sea thermal contrast during mid-Holocene summers (Zheng and Yu, 2009). In the East Asian monsoon region, the vertical and horizontal temperature gradient changes gave rise to a weakening and southward shifting of the subtropical westerly jet, which favored convergence in the upper troposphere and divergence in the mid-troposphere in North China. As a result, monsoonal rainfall was suppressed in North China but enhanced in South China. In earlier simulations with the Fast Ocean Atmosphere Model, SSTs were found to increase in the western North Pacific due to orbitally induced insolation changes, which reduced land–sea thermal contrast and, hence, monsoon circulation in East Asia during mid-Holocene summers (Liu et al., 2003b). Based on the same model, Li and Harrison (2008) revealed that ocean feedback dampened orbitally induced increases of summer precipitation in southeastern China, consistent with Liu et al. (2003b). These results were opposite to the aforementioned positive feedback of the ocean on the EASM (Wei and Wang, 2004; Zheng and Yu, 2009), implying an uncertainty in the effect of the ocean on the Asian climate during the Holocene, as discussed by Liu et al. (2003b) and Tian and Jiang (2013). How, and to what extent, the East Asian monsoon responded to mid-Holocene orbital forcing calls for further studies.

Change in the amplitude of El Niño and its link to the mean climatology of the mid-Holocene were examined using PMIP2 AOGCM simulations by Zheng et al. (2008). Most simulations reproduced the modern large-scale features of the tropical Pacific and ENSO variability. El Niño amplitude was shown to be an inverse function of the mean trade wind within the Niño4 region and the seasonal cycle relative strength, and to have a linear relationship with seasonal phase locking. All the AOGCMs reproduced a consistent El Niño weakening in the mid-Holocene, consistent with previous experiments (Liu et al., 2000). The associated mechanism was that, while the NH received more insolation in summer, the Asian summer monsoon strengthened and then led to an enhancement in Walker circulation, as discussed by Liu et al. (2000). Easterlies prevailing in the central eastern Pacific induced an equatorial upwelling, which dampened the development of El Niño.

3.1.4. *Mid-Holocene model–data comparisons in China*

Responding faithfully to the imposed mid-Holocene negative radiative forcing in China as derived from changes in the Earth's orbital parameters and atmospheric greenhouse gas concentrations, 35 of the 36 PMIP1/2 models reproduced colder-than-baseline annual and winter temperatures over the country (Jiang et al., 2012). By contrast, as discussed above, a variety of proxy data indicated warmer annual and winter temperatures in the mid-Holocene. Taken together, the results of 36 PMIP models were opposite to the multi-proxy records. On the whole, interactive vegetation had little effect on mid-Holocene temperature over China according to the six pairs of PMIP2 coupled models. Interestingly, an AGCM simulation with reconstructed vegetation was closer to proxy data. In particular, the simulated winter temperature increase of $\sim$ 0.5–1 K was more consistent with the value of $\sim$ 3 K suggested by proxy data in the mid-Holocene (Chen et al., 2002). On the other hand, 36 PMIP1/2 models indicated that an interactive ocean gave rise to an additional warming of 0.5 K in winter and 0.7 K in boreal autumn in China, and hence the annual and winter temperatures of coupled models were in better agreement with proxy data than those of atmospheric models during the mid-Holocene (Jiang et al., 2012). In summer, the results of 12 PMIP2 AOGCMs were consistent with reconstructed temperature in eastern China, but they failed to capture the strongest warming on the southern QTP (Wang et al., 2010). Compared with the wetter-than-present climates derived from the records at 64 out of 69 sites across China, 36 PMIP1/2/3 models agreed qualitatively with the multi-proxy data in most parts of China, except Xinjiang and the areas between the middle and lower reaches of the Yangtze and Yellow River valleys, where drier-than-baseline climates were obtained from the models (Jiang et al., 2013b).

3.2. ***Abrupt climate change in China at 4 ka BP***

3.2.1. *Evidence of abrupt climate change in China at 4 ka BP*

A significant cold and dry abrupt climate change event has been reported to have occurred at *ca.* 4 ka BP, which was possibly related to the collapse of ancient civilizations in the alternation of the ancient cultures in China (Wang et al., 2004). Proxy records at 80 sites, covering almost the entire Chinese territory, illustrate that humidity reduced along a band stretching from Southwest to Northeast China at that time, whereas archaeological evidence indicated that flooding was prominent in the lower reaches of the Yangtze River valleys (Wang et al., 2009a). Meanwhile, dramatic environmental changes occurred in the western Chinese Loess Plateau and corresponded with substantial changes in human demography at *ca.* 4 ka BP (An et al., 2005). A rapid climate transition from wet to dry led to a period of ecological devastation between 4.1 and 3.6 ka BP. The sudden reduction in the number of archaeological sites during that period—a reduction in the total number of sites and a contraction of the areal distribution of sites—pointed to a declining agricultural productivity associated with widespread aridification beginning at *ca.* 4 ka BP.

3.2.2. *Possible cause of abrupt climate change in China at 4 ka BP*

Holocene abrupt climate changes were mostly characterized by cold events in the North Atlantic. Sediment records in the North Atlantic have proven the occurrence of a cold event at 4 ka BP (Wang, 2009). It was therefore hypothesized that the abrupt drought event in China at 4 ka BP may relate to the cold event in the North Atlantic (Wang et al., 2009a). Wang et al. (2004) conducted sensitivity experiments to simulate global climate responses to the SST forcing in the North Atlantic, the geographical distribution of which stood for a typical weakening of the thermohaline circulation in the Atlantic Ocean. Results showed a drop of temperature in northern Europe, the northern central East Asia, and northern East Asia, and a significant reduction of precipitation in East Africa, the Middle East, the Indian Peninsula, the Yellow River valleys, and North China. These results seem to support the hypothesis that coldness and aridification in China at 4 ka BP was, at least partly, caused by the weakening of the thermohaline circulation.

Meanwhile, a set of numerical experiments revealed that changes in Earth's orbital precession could also have significantly affected summer precipitation in China during the Holocene (Wang et al., 2008b). More specifically, summer precipitation increased in the middle and lower reaches of the Yangtze and Yellow River valleys but deceased significantly in most parts of the rest of the mainland China, the pattern of which resembled the reconstructed environment at 4 ka BP. Taken together, the drought event in North China at 4 ka BP may have resulted from both abrupt climate change in the North Atlantic and the precession effect.

3.3. *Perspective*

The reconstruction and simulation of the Holocene climate are important for exploring natural variability and external forcing of the climate system on the orbital scale, and have become a central theme both in climate modeling and proxy data communities. As is well known, changes in orbital forcing are the main reason for the mid-Holocene climate having been significantly different from that of the present day. Based on records and simulations in China, we would like to emphasize that an interactive ocean appears to modify the response of climate models to mid-Holocene orbital forcing and give rise to more reasonable results in China as a whole. However, ocean feedback on the Asian monsoon climate still remains an open question, particularly in terms of the underlying dynamic mechanism. In addition, based on the earlier AGCM simulations, reconstructed vegetation appears to decrease surface albedo and lead to a surface warming in China; whereas, based on the six pairs of PMIP2 coupled models, interactive vegetation has little effect overall on mid-Holocene climate over the country. The extent to which vegetation varied and how it interacted with climate during that period should be specifically investigated in the context of cause and effect. Furthermore, it should be kept in mind that the results of the 36 PMIP models were opposite to warmer-than-present annual and winter climate conditions as derived from proxy data. At the moment it is unclear whether this inconsistency arises from the models, from the proxy data, or from both sides. If the interpretations of those proxy data are correct, a big question is why the PMIP models failed to reproduce the mid-Holocene East Asian climate. On the other hand, the PMIP models seem to do what is asked of them in terms of negative radiative forcing in China. Is it possible that the paleoarchives are not actually able to record the information that is equivalent to temperature in the models? Interestingly, mid-Holocene temperature was reconstructed to be colder in part of China in the works of Guiot et al. (2008) and Bartlein et al. (2011). More reconstruction work using multiple proxies and methods is therefore required to reduce the uncertainty of proxy data. Comprehensive comparisons between multiple climate models and multiple proxy records will ultimately reveal the nature and underlying mechanisms of mid-Holocene climate change in China.

The abrupt climate change that took place in China at *ca.* 4 ka BP was likely synchronous with that which occurred in the North Atlantic and the change in Earth's orbital precession. More simulations are needed to explore the reasons behind the event. In addition, transient simulations of the Holocene climate, together with its comparison with proxy data in China, remain an open field for climate modelers. Such studies will greatly improve our knowledge on Holocene climate change and events, such as those that occurred at *ca.* 8.2 ka BP and *ca.* 4 ka BP, and on the dynamic mechanisms operating at the regional and global scales during the Earth's recent history (e.g., Jin et al., 2005, 2009; Liu et al., 2009c).

4. LGM climate modeling in China

4.1. *Reconstructed LGM climate*

The LGM refers to the time when the ice sheets during the last glacial period were at their maximum extent, approximately 21 ka BP. This extreme period persisted for several thousand years, during which time global climate was very different to that of today (Jansen et al., 2007). Based on various proxies over China, the LGM generally featured cold and dry climates, with a spatial variability (e.g., Qin and Yu, 1998; Jiang et al., 2011). In western China, higher lake levels and fresher water than today reflected wetter conditions, whereas the opposite situation was recorded in most parts of eastern China at that time (Yu et al., 2003a). On the QTP, the LGM temperature was ~ 7 K colder than at present, while precipitation was only 30%–70% of the current level (Shi et al., 1997). In tropical areas of China, temperatures were 5–8 K colder than the present day, while precipitation was higher (Zheng and Guiot, 1999). Clearly, these reconstructions lay firm foundations for LGM East Asian climate modeling. By comparing simulations with reconstructions, it is possible to uncover the realistic characteristics of the LGM climate.

4.2. *LGM climate modeling*

4.2.1. *LGM boundary conditions*

The LGM was characterized by great changes in surface boundary conditions and atmospheric greenhouse gas concentrations, but minor changes in orbital forcing. Among these include changes in ice sheet extent and topography (Peltier, 1994, 2004), atmospheric CO_2 concentrations, and the Earth's orbital parameters (Berger, 1978). SSTs and sea ice extent are usually prescribed as in CLIMAP (Climate: Long range Investigation, Mapping, and Prediction) project members (1981) for AGCM experiments, but they are computed by slab ocean models or OGCMs in coupled model experiments. Variations in atmospheric CH_4 and N_2O concentrations were considered in part of the PMIP experiments. In East Asia, LGM vegetation compiled from pollen records has also been used in several experiments.

In fact, there are uncertainties in the earlier boundary conditions recommended by PMIP1. In particular, the SSTs established through the CLIMAP project were considered too high for the LGM, especially in the tropical Pacific and Atlantic oceans (e.g., Farrera et al., 1999; Mix et al., 1999). For example, the LGM SSTs compiled by Wang (1999b) differed largely from those of the CLIMAP project in the western Pacific. The former described a colder tropical western Pacific west of 130°E, with an annual decrease in SSTs of ~ 2 K, and a warmer ocean current near Japan. In particular, the LGM annual mean SSTs established by Wang (1999b) for the tropical western Pacific west of 140°E were 2–4 K lower than at present. To what extent these reconstructed SSTs potentially affected the East Asian climate remains of interest.

4.2.2. *LGM climate in China from global climate models*

4.2.2.1. LGM climate in China

In the early 1990s, a two-level AGCM, constructed at the Institute of Atmospheric Physics (IAP) under the Chinese Academy of Sciences, was used to investigate the LGM July climate with CLIMAP boundary conditions and atmospheric CO_2 concentrations of 200 ppmv (Wang and Zeng, 1992b). The later version of that model, hereafter referred to as IAP-AGCM, was also used to simulate the LGM climate within PMIP1 (Jiang et al., 2003). It reproduced colder and drier climates, with a global annual temperature of 5.3 K less, and a terrestrial precipitation level of 29% less, than at present. In East Asia, both annual temperature and precipitation reduced during that period, which were basically consistent with proxy data (Shi et al., 1997; Farrera et al., 1999; Liu et al., 1999). Another set of AGCM experiments indicated that the LGM featured drier conditions in the east and wetter conditions in the west, while the East Asian monsoon weakened significantly (Chen et al., 2000, 2001). Using the same AGCM, Liu et al. (2002a) further showed that the LGM annual temperature decreased by 2–13 K in China. Summer and annual precipitation in eastern China were only $\sim 50\%$ of current levels, whereas precipitation differing little or not at all was found for western China.

Based on the Community Climate Model version 3 (CCM3) AGCM experiments with the SSTs reconstructed by Wang (1999b) for the tropical western Pacific and reconstructed vegetation, it was shown that winter monsoon strengthened notably in northern China, while summer monsoon weakened notably in the South China Sea and southern China during the LGM (Zhao et al., 2003). For that period, annual temperature and precipitation reduced in East Asia, with the greatest decrease in precipitation in eastern Tibet, on the Chinese Loess Plateau, and in northern China, causing surface soil to lose water and become dry. On the central QTP, surface soil lost less water and became wetter. This process may explain why the LGM water levels in the lakes of the central QTP were higher than at present (Yu et al., 2003a). Owing to an increase in snowfall during the LGM, the depth of snow cover increased remarkably in the southern QTP, which provided favorable conditions for the expansion of local glaciers.

A comparison of tropical atmospheric heating and circulation patterns between the LGM and the present day was carried out by Zhao et al. (2004). The largest decrease in atmospheric heat occurred in the tropical regions stretching from the Bay of Bengal to the central Pacific Ocean, while there were no significant changes at higher latitudes. This indicated that atmospheric heat in the tropics showed a stronger response to the boundary condition changes between the LGM and the present day than it did at higher latitudes, since the tropical convection amplified the response of the atmosphere in the former case. Because of this tropical heat change, the LGM Walker circulation, the transverse monsoon, and the EASM were weaker than at present.

Besides experiments from individual climate models, the results of 25 PMIP1/2 models have also been used to examine the LGM regional climate of China (Jiang et al., 2011). Compared to the baseline climate, annual temperature was decreased by 2–7 K in China, with an average of 4.5 K, for the 25-model ensemble mean. The LGM annual precipitation and evaporation were 5%–40% less than the baseline levels based on the results of 15 climate models that were selected for their ability to simulate the modern precipitation climatology. Both the geographical distribution and magnitude of changes in temperature, precipitation, evaporation, and effective precipitation varied with the seasons and with the models, particularly at the sub-regional scale. In contrast to the conclusions drawn from sparse proxy data, the intensity of the East Asian winter monsoon during the LGM, as measured by regionally averaged meridional wind speed at 850 hPa, was found to vary both in sign and magnitude, with reference to the baseline period, across the PMIP simulations (Jiang and Lang, 2010). It weakened by 4% for the 21-model ensemble mean and by 15% for the ensemble mean of 14 coupled models. At the sub-regional scale, the LGM winter monsoon strengthened north of ~ 30°N but weakened south of this region in East Asia. During LGM summers, all of the 14 models chosen for analysis consistently simulated a weaker-than-baseline East Asian monsoon, with an average weakening of 25%. Changes in zonal and meridional land–sea thermal contrast across the regions of concern were responsible for those changes in the LGM East Asian monsoon.

4.2.2.2. Effects of western Pacific SSTs and an interactive ocean

The effect of LGM SSTs in the tropical western Pacific, as reconstructed respectively by Wang (1999b) and CLIMAP, was evaluated using the CCM3 AGCM by Zhao et al. (2004). The latter led to larger changes in atmospheric circulation in the tropics and high northern latitudes, reproducing a weaker transverse monsoon and a larger seasonal variation of the Walker circulation, with lower temperature in the high northern latitudes and the Arctic and lower temperature in the coldest month in Europe. Winter temperature was reduced by 4 K in Europe, which was closer to pollen-based reconstructions. Additionally, there was a smaller effect of the western Pacific SSTs on temperature in the SH during the LGM.

The Asian summer monsoon was also sensitive to the differences in LGM SSTs (Sui and Zhao, 2005). In response to warmer summer SSTs in the tropical western Pacific (Wang, 1999b), the South Africa high and Hadley circulation over the South Indian Ocean intensified, with a stronger zonal monsoon circulation in the Indian monsoon areas. Accordingly, the Indian summer monsoon intensified, with a strengthened level of water vapor transportation and more precipitation in the Indian monsoon areas. In the East Asian monsoon region, the Wang (1999b) SSTs caused a weaker Australian high, with a weakened cross-equatorial current in East Asia and zonal monsoon circulation north of 20°N. These features demonstrated a weaker East Asian subtropical continental monsoon and a stronger South China Sea monsoon. Moreover, Wang et al. (2009b) examined the effect of LGM SSTs in the tropical Atlantic and eastern equatorial Pacific, reconstructed respectively by Mix et al. (1999) and CLIMAP, on the Pacific convergence zone. It was found that the different constructions of the tropical SSTs in the Pacific and Atlantic oceans caused large uncertainties in simulating the LGM climate. Thus, resolving the apparent disagreements among the different SST reconstructions is necessary.

Within the PMIP1/2, annual surface cooling over China was stronger in coupled models than in atmospheric models (Jiang et al., 2011). Less surface cooling in the latter was, at least partly, attributed to the small reductions in the CLIMAP reconstructed SSTs in the oceans adjacent to the East Asian continent. In the western North Pacific, for example, the LGM changes in regionally averaged annual SSTs from the experiments of six PMIP2 AOGCMs were colder than the CLIMAP SSTs used as boundary conditions of the PMIP1 AGCMs. Accordingly, the LGM annual surface cooling over China was larger in the AOGCM experiments, because the corresponding colder SSTs in the western North Pacific gave rise to larger losses of surface heat in the East Asian region during warm months and smaller gains of surface heat during cold months. Since the simulations of coupled models are in better agreement with proxy estimates than those of atmospheric models, interactive ocean appears to be an important component of the LGM climate system in the East Asian monsoon region.

4.2.2.3. Effect of vegetation

A series of sensitivity experiments revealed that reconstructed vegetation could exert strong effects on the LGM climate in China (Chen et al., 2000, 2001; Yu et al., 2001; Liu et al., 2002a); in particular, on the QTP, changes in vegetation increased the differences in temperature, precipitation, and effective precipitation between winter and summer. Based on global paleovegetation compiled from pollen records, the simulations undertaken by Yu et al. (2003a) reproduced lower temperature and precipitation in eastern China, with positive precipitation in western China more extensively. In general, the effect of vegetation contributed to an increase in both the aridity in eastern China and the humidity in western China during the LGM. Compared to proxy data, additional climate change due to vegetation generally reduced model–data discrepancies in East Asia.

The influence of reconstructed vegetation (Yu et al., 2000) and associated soil characteristics on the LGM East Asian climate was further examined by Jiang et al. (2003). Sparser-than-present paleovegetation enlarged regional surface albedo, and hence temperature decreased. As a result, model–data discrepancies in temperature were partly reconciled. Using different vegetation reconstructions in China was found to cause large uncertainties in simulating the East Asian summer climate (Han et al., 2009). Relative to the present day, the degradation of vegetation during the LGM over China increased local surface temperature during summer, strengthening the thermal contrast between the East Asian continent and the adjacent oceans. Accordingly, the summer southwest monsoon strengthened during the LGM. In terms of the climatology, when southwesterly winds weaken (strengthen), the rain belt in front of the maximum southwesterly wind center often stays in a more southward (northward) position, leading to more (less) rainfall in southeastern (northern) China (Zhao et al., 2007, 2010). Thus, corresponding to the strengthened southwesterly winds caused by the vegetation change, there is an increase in summer rainfall over northern China and a decrease in rainfall over southeastern China. In this context, reconstructing more believable vegetation over East Asia is important to reduce the uncertainties due to vegetation.

IAP-AGCM and its asynchronously coupled system with an equilibrium terrestrial biosphere model were used to further investigate vegetation and soil feedbacks during the LGM (Jiang, 2008). The simulated vegetation differed largely from the present day, and global vegetation cover tended to be reduced overall in adaptation to colder and drier climates. Vegetation feedback induced an annual temperature decrease of 0.31 K, mainly through changes in surface albedo, on the LGM's ice-free continental areas. Additional soil feedback reinforced vegetation-induced cooling through surface albedo in the high latitudes of Eurasia and from the eastern Middle East eastward to the Indian Peninsula. In the tropics, a terrestrial annual cooling of 0.45 K was derived from vegetation and soil feedbacks. They partly reduced model–data discrepancies in Central Africa, the Indian Peninsula, South China, North Australia, etc. Meanwhile, inter-model comparisons have also shown that there were large uncertainties with respect to the LGM vegetation feedback, particularly at the regional scale (Jiang, 2008). In the experiments of the UK Meteorological Unified Model run at Bristol University, vegetation feedback was found to give rise to an annual cooling of 2 K, with a seasonal and regional variability, over China during that period (Jiang et al., 2011). In this regard, the extent to which vegetation feedback behaves in fully coupled atmosphere–ocean–vegetation models needs to be further explored.

4.2.3. *LGM East Asian climate from regional climate models*

Using a regional climate model nested within an AGCM, Qian et al. (1998) simulated the LGM July climate of East Asia. Later, the regional climate model RegCM2, with a 120 km horizontal resolution, was used to reproduce the LGM East Asian climate (Zheng et al., 2003, 2004). Those experiments provided more details of the East Asian climate, with respect to global models, particularly in understanding the processes behind the LGM East Asian monsoon changes. Based on the improved version of RegCM2 with a 60 km horizontal resolution, Ju et al. (2007) further examined the LGM East Asian climate, in which the 12-hourly updated lateral boundary conditions were provided by IAP-AGCM. Their simulations indicated that LGM annual temperatures were 2–4 K colder overall than at present over the East Asian continent, with the largest decrease of ~ 8 K in the vicinity of the current coastal areas, where land was exposed due to sea level lowering. Compared to the results of IAP-AGCM alone, RegCM2 simulations were more consistent with proxy data in East Asia, especially in central-eastern and southern China where RegCM2 simulated a colder LGM climate. Annual precipitation decreased by $\sim 60\%$ in the drier-than-present areas of China in RegCM2, which was also closer to proxy records than in IAP-AGCM.

Meanwhile, a 90 km horizontal resolution mesoscale model was nested within an AGCM to evaluate the effect of the LGM boundary conditions on the East Asian climate (Liu et al., 2007a, 2007b). Changes in atmospheric CO_2 concentrations were found to have a significant influence in winter but less of an impact in summer during the LGM. Compared to the present, the LGM changes in sea–land distribution in East Asia resulted in a decrease in temperature in winter but an increase in summer, with a decrease in annual precipitation by 25%–50% in the coastal areas of East Asia.

4.2.4. *LGM environment on the QTP*

There is debate on the existence of a unified ice sheet on the QTP during the ice age. Using proxy data, Liu et al. (1999, 2002b) examined the glacial environment on the QTP and proposed a relatively large area of snow and glaciers on the plateau. Based on a relationship between summer temperature and annual total precipitation at the equilibrium line altitude of glaciers in western China, Zhao et al. (2003) used CCM3 AGCM results to analyze the glacial environment. It was shown that, as a result of balance between precipitation and temperature, the LGM equilibrium line altitude of glaciers on the QTP was 300–900 m lower than at present, which indicated the existence of a large-scale continental ice sheet on the plateau during that period. Later, Jiang et al. (2004) utilized an equilibrium terrestrial biosphere model to simulate the LGM environment in China. It was found that ice covered almost half of the QTP.

As a further step, Jiang et al. (2003) evaluated the potential influence of the QTP ice sheet on the LGM climate of East Asia. When the ice sheet was assumed, the strongest temperature changes of around -7 K appeared in the central-western part of China during the LGM. The existence of the QTP ice sheet induced an additional regional cooling in East Asia, leading to a strong anomalous anticyclone near the QTP in summer and a weak EASM. Meanwhile, the subtropical high over the western North Pacific moved southeastward and precipitation decreased in the central-eastern part of China. Therefore, if a suitable area of ice sheet appeared on the QTP, a lower temperature would be presented in East Asia, which would improve the LGM temperature simulation in East Asia with respect to proxy data.

4.3. ***LGM Model–data comparisons in China***

As previously mentioned, various experiments have been performed to examine the LGM climate in China. Generally, they can reasonably reproduce colder- and drier-than-present climates over the country during that period. Quantitatively, however, model–data differences are still remarkable at the regional scale. In the results of 25 PMIP1/2 models, the LGM regionally averaged annual temperature was reduced on average by 3.4 K in South China, 5.1 K on the QTP, 4.7 K in the Hexi Corridor, and 4.9 K in North and Northeast China. All of them were smaller than the corresponding reconstructed levels of 7.0 ± 3.5 K, 6–9 K, 13–15 K, and at least 8–10 K as derived from a variety of proxy records (Jiang et al., 2011). On the other hand, LGM annual precipitation minus evaporation changes from the results of 15 PMIP1/2 models agreed qualitatively with lacustrine records, including drier conditions in eastern China and wetter conditions in the region of (35°–42°N, 74°–97°E). By contrast, model–data disagreements occurred on the QTP and in most parts of northern Xinjiang, where simulated drier conditions were opposite to lacustrine records. On the eastern QTP, drier climates agreed with pollen records but disagreed with lacustrine records. In short, the PMIP models successfully reproduced the LGM surface cooling trend over China but failed to reproduce its magnitude, while their humidity results qualitatively agreed with lacustrine records over China excluding the QTP and northern Xinjiang. These model–data discrepancies possibly arose from uncertainties in the boundary conditions (including tropical SSTs for atmospheric model experiments, vegetation conditions, the environment on the QTP, etc.) used in simulations (Jiang et al., 2003; Zhao et al., 2003). For instance, the ability to simulate temperature change could be improved by replacing local vegetation with continental ice on the QTP. In addition, discrepancies in physical processes between climate models could be important contributors to the differences among simulations.

4.4. *Perspective*

LGM climate simulations and comparisons with proxy data have improved our knowledge of the features and dynamic mechanisms relating to ice age climates. Based on the PMIP protocol, Chinese scientists have further designed unique experiments to reveal that feedback mechanisms concerned with vegetation, the effect of Pacific and Atlantic SSTs, and the influence of the QTP environment are all important factors and should be evaluated comprehensively in LGM climate simulations. At this point it is important to reiterate that, due to different boundary conditions used in simulations, the features of the LGM climate have appeared, to some degree, to be divergent. In fact, distinct differences in the response of the LGM climate have been found in various models, albeit when the same or similar boundary conditions were employed (Jiang et al., 2011). To narrow those uncertainties, many improvements are required in the future, not only in terms of proxy data, to verify simulated results, but also in the properties of climate models themselves, including the accuracy of boundary conditions. Issues relating to the importance of unique boundary conditions should also be examined in depth. For example, it is necessary to systematically consider vegetation–climate feedback, to analyze the impact of different SST reconstructions in some key regions, and to evaluate glacial environments on the QTP and their climatic consequences.

5. Late MIS3 climate modeling

5.1. *Reconstructed late MIS3 climate in China*

The late MIS3 refers to the period *ca*. 30–40 ka BP, at which time global temperature was lower than in the last interglacial period and the Holocene, but slightly higher than in the early and late last glacial (Yang et al., 2004, and references therein). At the regional scale, however, climate was warmer and wetter in western China, with an estimated annual temperature that was 2–4 K higher on the QTP at that time than at present (Yao et al., 1997; Shi et al., 2001; Shi and Yu, 2003; Yang et al., 2006; Yu et al., 2007). Such a situation raises an interesting question: why was regional climate change in China so different from that at the global scale? Examining the response of climate models to the boundary conditions at 35 ka BP and its consistency with proxy data are helpful for understanding East Asian climate change on the orbital scale.

5.2. *Late MIS3 boundary conditions*

Changes in the Earth's orbital parameters are believed to be the most important forcing for climate change during the late MIS3 (Shi et al., 2001; Shi and Yu, 2003). Ice sheet extent at 35 ka BP is prescribed as 50% of the area of ice sheets at 21 ka BP according to glacial sediments (Lambeck and Chappell, 2001), with the height of the remaining ice sheets kept the same as at 21 ka BP (Peltier, 1994). Vegetation in China at 35 ka BP has been reconstructed based on pollen and macrofossil data, showing that forests in southeastern China extended northwards into the present northwestern steppe region, while the northern boundary of tropical forests in southern China shifted north of 24°N (Shi et al., 2001). Atmospheric CO_2 concentrations were set to 210 ppmv at 35 ka BP from the present value of 345 ppmv.

5.3. *Climate modeling for 35 ka BP*

A set of AGCM experiments showed that the climate at 35 ka BP featured warm–wet conditions in northern China and warm–dry conditions in southern China compared to the present day (Yu et al., 2003b, 2005, 2007). Annual temperature was higher in most mid- and lower latitudes of East Asia, which was mainly the result of increased winter temperature. During winter, although insolation in the mid and lower northern latitudes decreased, changes in vegetation in East Asia led to more heat storage and less reflection of radiation, while they also suppressed cold airflow and hence reduced the likelihood of temperature falling. In this sense, reconstructed vegetation modified the climate model response to orbital forcing through the coupling of atmospheric circulation with land surface conditions. In addition, the ice sheets of the NH during the Quaternary were also found to play an important role in the temperature drop at the mid-high northern latitudes and also to enhance the south–north temperature gradients, which in turn increased moisture transport from low to high northern latitudes and increased monsoonal precipitation on the QTP. Vegetation changes in East Asia were inferred to result from increased temperature in the low latitudes, an extended rain belt northwards into China, and an enlarged area of increased precipitation inland.

During summer, precipitation was significantly increased in the East Asian monsoon region, which was directly related to an enhanced monsoon due to increased heating contrasts between high and lower latitudes under larger latitudinal gradients of insolation and stronger ice sheet impacts at 35 ka BP than at present. Meanwhile, at 35 ka BP the summer sea level pressure difference between the Pacific Ocean and Asian continent was 3–6 hPa above the present day. This pattern also increased the strength of the Asian summer monsoon and therefore increased regional precipitation. During winter, the high pressure system in East Asia weakened, while the Aleutian low pressure system in the northern North Pacific Ocean strengthened at 35 ka BP with respect to the present day. The decreased difference in the land–sea pressure gradient reduced the winter vapor exchange between land and sea. This caused a winter precipitation decrease in eastern China. Meanwhile, the Siberian high pressure center was relatively weak, weakening the East Asian winter monsoon and the incursion of cold air.

5.4. *Model–data comparisons in China*

It should first be noted that qualitative temperature and/or precipitation estimates for the late MIS3 are based on the views of the original authors who reconstructed the climate from various climate proxies. Since the authors did not al-ways specify if the estimates were for the annual or seasonal mean, we assumed they represented a mean status for a relatively long time interval. At 35 ka BP, geological records have indicated a mean temperature of ~ 2 K higher in western Tibet and northwestern and southern China, but little change in eastern China and a 1–4 K decrease in southwestern China and on the eastern QTP. The simulated temperature was compatible with proxy data, showing a 1–3 K increase in northeastern, northern, and western China and a drop in southwestern China. Reconstructed annual precipitation at 35 ka BP was increased over much of China, with values exceeding 300–500 mm in the western QTP, the Tsaidam Basin, and the Yunnan Plateau, and with values of ~ 0.5–1.0 mm d^{-1} higher than at present in western, central, and northeastern China. The simulated precipitation increase in central and western Tibet and Inner Mongolia was consistent with major patterns as seen in geological records. The simulated precipitation decreases in southeastern China were difficult to validate, since proxy data coverage was insufficient there.

In terms of regional comparisons at 35 ka BP, the simulated significant warm–wet pattern on the QTP agreed with lacustrine sediment records (Shi et al., 2001; Yang et al., 2004), while the warm–wet pattern on the Loess Plateau compared well to paleosol records (Guo et al., 1994; Chen et al., 1997). By contrast, the warm–dry conditions simulated for the eastern coastal plains of China disagreed with vegetation and climate reconstructions (Zheng and Zhou, 1995). Additionally, geological records showed significantly warmer and wetter conditions in northwestern China (Yang et al., 2004), whereas the simulations only reproduced a temperature increase, while precipitation was slightly changed.

5.5. *Perspective*

In response to the changes in solar radiation, glaciation in the NH, and East Asian vegetation at 35 ka BP, preliminary experiments showed that both temperature and precipitation increased in northern China, while temperature rose and precipitation decreased in southern China. The QTP underwent a temperature drop and a precipitation increase. Mechanistically, the temperature gradient between inland Asia and low-latitude oceans enlarged, and the transportation of water vapor from the ocean to the continent strengthened, thus increasing precipitation for inland China. At that time, vegetation change had an amplifying effect for orbital forcing through surface albedo. It caused temperature increases in the lower northern latitudes, a weakened temperature gradient in the high northern latitudes, an enlarged area of increased precipitation in inland Asia, and an extended rain belt northwards in China. In general, the influence of the Quaternary ice sheets in northern Europe and North America on the East Asian climate was weak. In future simulations, more climate models should be used to reduce model-dependent uncertainty, and current Earth system models should be used to investigate the effect of ocean and vegetation feedbacks on the East Asian climate during the late MIS3.

6. Pre-Quaternary climate modeling

6.1. *Mid-Pliocene climate modeling*

6.1.1. *Reconstructed mid-Pliocene climate*

The mid-Pliocene was *ca.* 3.29–2.97 Ma BP. This most recent warm interval in geological time provides a unique opportunity to improve our understanding of a warmer-than-present climate, which is expected to be similar in many ways to the 21st century climate being predicted by climate models, as a result of anthropogenic activity (Jansen et al., 2007). Various proxies suggest that the mid-Pliocene climate, compared to the present day, was characterized by a greatly reduced continental ice volume, greatly reduced sea ice, with the Arctic being seasonally ice free, a sea-level rise of 25 m, increased SSTs in the high latitudes and little or unchanged SSTs in the lower latitudes, and the presence of warmth and/or moisture-loving vegetation in the middle to high latitudes and a reduction of desert area in equatorial Africa (Dowsett et al., 1999). In addition, at that time, the land–sea distribution and geographical configuration were similar to the present day, atmospheric CO_2 concentrations were estimated to be about 35% higher than the pre-industrial value of 280 ppmv (Raymo et al., 1996), and continental aridity was lower (Guo et al., 2004).

6.1.2. *Mid-Pliocene climate modeling*

Under the mid-Pliocene boundary conditions, IAP-AGCM was used to simulate the mid-Pliocene climate, with particular attention paid to the East Asian climate (Jiang et al., 2005). The mid-Pliocene surface conditions were provided by the U. S. Geological Survey's Pliocene Research, Interpretations, and Synoptic Mapping (PRISM) group, i.e. the PRISM2 $2^\circ \times 2^\circ$ digital dataset (Dowsett et al., 1999). They were composed of monthly SSTs and sea ice extent, continental topography, vegetation, and continental ice sheet coverage.

A set of simulations indicated that warmer- and wetter-than-present climates prevailed during the mid-Pliocene (Jiang et al., 2005). Global annual temperature rose by 2.6 K, with a stronger warming in the high latitudes. Changes in SSTs and sea ice extent were mainly responsible for the simulated warming. The effects of vegetation and continental ice sheet changes played an important role in part of the middle to high latitudes, although their global influence was quite limited. Global annual precipitation increased by 4.0%, with a larger increase in the high latitudes. On the contrary, drier conditions occurred in most parts of 0°–30°N, consistent with the weakening of tropical Walker circulation and the poleward expansion of Hadley cells (Sun et al., 2013). In addition, both summer and winter monsoons weakened significantly in East Asia, which resulted from a weakened thermal contrast and, in turn, a decrease in sea level pressure gradient between the East Asian continent and the adjacent oceans. Based on Chinese red clay sequences, An et al. (2001) reconstructed a weaker-than-present East Asian monsoon during 3.6–2.6 Ma BP and related it to the extent and height of the Himalaya–Tibetan Plateau. The present simulations revealed that the changes in SSTs and sea ice extent can also lead to such changes. Therefore, particular attention should be given to oceanic behaviors when exploring the Pliocene climate of East Asia. In addition, the simulated mid-Pliocene vegetation differed from the present day over 62% of the global ice-free land surface (Jiang, 2013). Vegetation feedback had little overall impact on the global climate of the mid-Pliocene. At the regional scale, however, interactive vegetation led to statistically significant increases in annual temperature over Greenland, the high latitudes of North America, the mid-high latitudes of eastern Eurasia, and western Tibet, and reductions in most of the land areas at low latitudes, owing to vegetation-induced changes in surface albedo.

Inter-model comparisons indicated that IAP-AGCM results were overall compatible with earlier simulations. The simulated mid-Pliocene warming varied from 1.4 K using the GISS (Goddard Institute for Space Studies) AGCM (Chandler et al., 1994), to 1.9 K using the UKMO (UK Meteorological Office Unified Model) AGCM (Haywood et al., 2000), to 2.6 K using IAP-AGCM, and to 3.6 K using the GENESIS (Global Environmental and Ecological Simulation of Interactive Systems) AGCM (Sloan et al., 1996). The geographical distribution of the warming was also broadly consistent among the models. Meanwhile, all the models simulated a slightly wetter climate for the mid-Pliocene. In East Asia, the UKMO AGCM produced significantly reduced summer precipitation and an increase over part of the QTP, which agreed with IAP-AGCM results. Additionally, the mid-Pliocene annual precipitation decrease over much of East Asia in the GENESIS AGCM was also consistent with the results of IAP-AGCM.

6.1.3. *Model–data comparisons in China*

IAP-AGCM simulations indicated that, except for on the QTP where annual temperature declined due to changes in topography, annual temperatures rose by 4–8 K in eastern China and 1–4 K in western China, with respect to the present day. Annual precipitation reduced largely in eastern China, with an average of above 0.5 mm d^{-1}, particularly in the middle reaches of the Yangtze River valleys. Meanwhile, annual precipitation increased slightly in northern Xinjiang, Qinghai, and most parts of Tibet, whereas it reduced in central and southern Xinjiang.

Available proxy data consistently suggest that the mid-Pliocene was warmer (e.g., Han et al., 1997; Ding et al., 1998), and that the East Asian winter monsoon was weaker than at present (e.g., Ding et al., 1998; An et al., 2001; Wehausen and Brumsack, 2002; Tian et al., 2004; Sun and Wang, 2005; Wan et al., 2007; Sun et al., 2008). Therefore, both the warming and weakening of the East Asian winter monsoon as simulated by IAP-AGCM agreed with proxy data. In contrast, both drier (Han et al., 1997; Wu et al., 2006) and wetter (Ding et al., 1998; Li et al., 2004) climates were reconstructed for the mid-Pliocene by loess-paleosol and red clay sequences from the Chinese Loess Plateau, although the locations of the sample sections were close. Additionally, most proxy data suggest a weaker-than-present EASM (Tian et al., 2004; Wang and Deng, 2005; Wu et al., 2006; Wan et al., 2007). However, a similar (Ding et al., 1999), similar or slightly stronger (Wehausen and Brumsack, 2002), and stronger (Ding et al., 2005; Sun et al., 2008) EASM has also been reported, and the mid-Pliocene EASM was shown to strengthen in recent multiple models (Zhang et al., 2013b). This means there are large uncertainties in the changes of mid-Pliocene precipitation and EASM, and the extent to which IAP-AGCM-simulated aridity and EASM weakening are compatible with proxy data remains an open question, even in a qualitative sense.

6.1.4. *Perspective*

Global mean temperatures rose by 0.74 ± 0.18 K during the period 1906–2005 (Trenberth et al., 2007), and global emissions of greenhouse gases are expected to lead to a continued and strengthened warming in the future. Based on a variety of emissions scenarios for atmospheric greenhouse gases and aerosols, globally averaged temperature is projected to increase by 1.1–6.4 K by 2090–99, relative to 1980–99 (Meehl et al., 2007). However, the spatiotemporal pattern of the warming and the dynamic mechanism responsible for the current and forthcoming warming are highly uncertain. At this point it is of interest to examine the mid-Pliocene climate because it is thought to be similar to the model-based climate projections for the 21st century. Moreover, a variety of proxy data are available and well constrained for that period. In general, investigation of the mid-Pliocene climate can provide insights into a warmer-than-present climate regime. They can also help to assess the ability of climate models to reproduce a warm climate and examine the sensitivities of climate models to different boundary conditions and the associated feedbacks that may be operating in a warm climate regime, particularly when investigating climate model sensitivity to an elevated atmospheric CO_2 scenario. And finally, they can help to interpret the mid-Pliocene geological records.

6.2. *Influence of continental changes on climate*

The present tropical Pacific Ocean is largely characterized by a strong temperature gradient between the warm pool in the west and the cold tongue in the east. In particular, the western Pacific warm pool (WPWP) is a region with the highest SSTs of all the oceans, and is also a region with the strongest mass and energy exchanges between the atmosphere and ocean. This region therefore has an important impact upon global climate on the seasonal and longer scales. However, proxy data indicate that the WPWP did not come into existence until *ca.* 10 Ma BP, and the present WPWP was formed only at *ca.* 3 Ma BP (e.g., Wang, 1994; Chaisson and Ravelo, 2000). Some researchers suggest that there was a close relationship between the formation of the WPWP and continental drift because the Australian and South American continents moved away from the Antarctic continent and drifted slowly northward since the late Tertiary, which finally resulted in the closure of the Indonesian seaway linking the Pacific and Indian oceans, and the closure of the Isthmus of

Panama linking the Pacific and Atlantic oceans (Zhou et al., 2004b).

6.2.1. *Impact of the closure of the Indonesian seaway on climate*

Using an AOGCM and its oceanic component OGCM, Yu et al. (2003c) performed numerical experiments to address the climatic consequences of the closures of the Indonesian seaway and the Isthmus of Panama. According to geological records of plate tectonics (Zhou et al., 2004b), topographical conditions at 6 Ma BP and 14 Ma BP were first compiled. After that, sensitivity experiments using the above continental configurations were respectively carried out by use of the OGCM. Additionally, Yu et al. (2003c) also used the AOGCM to perform the same four experiments with topography set to that of the present day, at 6 Ma BP, at 14 Ma BP, and at 14 Ma BP, except with the opening of the Isthmus of Panama factored in, respectively. Meanwhile, to investigate the effect of the northward shift of the Australian continent on tropical oceanic circulation and the SH climate, Zhou et al. (2004a, 2005) employed the GISS AOGCM to perform two experiments with the Australian plate configuration at 14 Ma BP and at present, respectively.

In the OGCM experiments, the closure of the Indonesian seaway had significant impacts on oceanic circulation in the tropical Indian and Pacific oceans (Yu et al., 2003c; Jian et al., 2006). At present, the equatorial undercurrent, which is composed of North Pacific water and South Pacific water that turns eastward in New Guinea, flows eastward and then upwells in the eastern equatorial Pacific at a subsurface layer. When the Australian plate lay south of its present position and the Indonesian passage accordingly became wider at 14 Ma BP, most of the water from the South Pacific passed through the Indonesian passage and entered directly into the Indian Ocean. Thus, the contribution of southern equatorial water to the equatorial undercurrent became less than at present. Since South Pacific water was generally warmer than North Pacific water, the simulated equatorial undercurrent, which was mainly supplied by water coming from the North Pacific at 14 Ma BP but from the South Pacific at present, was 1–2 K warmer in the equatorial Pacific but ~ 1 K colder in the equatorial Indian Ocean at present than at 14 Ma BP. In addition, more net heat energy entered into the surface of the equatorial Pacific. Furthermore, the AOGCM experiments reproduced similar results as obtained by the above OGCM.

The Australian Plate drift at 14 Ma BP also had significant impacts on atmospheric circulation and climate in the middle and high southern latitudes (Zhou et al., 2004a, 2005). Compared to the present, both anticyclonic circulations over subtropical oceans and cyclonic circulations around 60°–70°S were intensified. Thus, subtropical highs and circumpolar lows strengthened, which resulted in a stronger Antarctic Oscillation at 14 Ma BP. Precipitation and temperature also varied correspondingly. Precipitation decreased at around 40°S but increased at around 60°–70°S, while temperatures rose in the high latitudes of the South Pacific but descended over the Weddell Sea and its northern side. In addition, due to the changes in temperature and atmospheric circulation, sea ice extent increased in the Ross Sea and its western side, but decreased in the Weddell Sea.

6.2.2. *Effect of the closure of the Central American seaway on climate*

The closure of the Central American seaway or the Isthmus of Panama could also have played an important role in the formation of the present tropical oceanic and atmospheric circulations. The AOGCM experiments showed that the closure of the Isthmus of Panama was important in forming the present WPWP (Yu et al., 2003c; Jian et al., 2006). The emergence of the Isthmus of Panama was found to induce strong upwelling and uplift of the thermocline in the eastern equatorial Pacific, but a remarkable decrease of the thermocline in the western Pacific. As a result, the closure of the Isthmus of Panama isolated heat exchange between the Pacific and Atlantic oceans, led to a cooling of SSTs and an uplift of the thermocline in the eastern Pacific, and hence increased the contrast of heat content between the western and eastern Pacific. The amplitudes of thermocline depth changes between the two experiments indicated that the closure of the Panama seaway played an important role in the evolution of the WPWP. On the whole, this set of experiments implied that the closure of the Indonesian seaway could have resulted in the beginning of the WPWP, but the final formation of the WPWP was most probably induced by the closure of the Panama passage.

6.2.3. *Model–data comparisons*

Using marine sediments from the South China Sea and other lines of evidence, Jian et al. (2006) proposed three stages of WPWP evolution. The first was the beginning of the WPWP during 11.5–10.6 Ma BP. This period was coincident with the significant narrowing or partial closure of the Indonesian seaway between the Pacific and Indian oceans, although the timing of the closure of the Indonesian seaway is still a point of vigorous discussion. The second was the remarkably weakened or extremely unstable WPWP during 10.6–4.0 Ma BP. And the last was the formation of the present WPWP at *ca.* 4.0–3.2 Ma BP based on the significant increases in the south–north thermocline gradient of the South China Sea and the west–east thermocline gradient of the equatorial Pacific, which is often linked with the closure of the Panama passage, as discussed in Jian et al. (2006). The aforementioned simulations support the notion that the formation of the present WPWP depended strongly on the drift of the continents. However, it should be noted that only the reconstructed topography around the Indonesian and Central American seaways at 14 Ma BP was considered in those experiments. Besides the uncertainties in the history of the seaways, other changes in the QTP, glaciation in the NH, greenhouse gases, etc., also affected global and regional climates during the late Cenozoic. It is necessary to reconstruct a more complete picture of boundary conditions to accurately estimate the effect of continental drift on oceanic and atmospheric circulations using climate models.

6.3. *Climatic consequences of the QTP uplift during the late Cenozoic*

6.3.1. *Introduction*

The uplift of the QTP was a major event in the natural history of the Earth. A large quantity of geological evidence indicates that the northward drift of the Indian–Australian Plate and its collision with the Eurasian Plate caused a gradual uplift and the formation of the QTP during the late Cenozoic (Molnar, 1989; Ruddiman et al., 1989). Chinese scientists have studied the uplift of the QTP and the history of the East Asian monsoon based on various lines of geological evidence (e.g., An, 2000; Wang et al., 2005). For example, using records of aeolian sediments from Chinese loess and marine sediments, An et al. (2001) proposed three stages of evolution of Asian climate since the late Miocene and their relationship with the phases of the Himalayan–Tibetan Plateau uplift and NH glaciation. Although there is debate regarding the uplift processes of the plateau among the international academic community (e.g., Harrison et al., 1992; Li and Fang, 1999; Harris, 2006; Wang et al., 2008a), there is no dispute that the plateau uplift had significant influences on global and Asian climates throughout the Cenozoic era. The profound impact of the QTP uplift on the evolution of the Asian monsoon is now being widely recognized.

The important role of the QTP in controlling the Asian climate has been known for a long time. Flöhn (1968) was among the first to point out the significance of the QTP in maintaining the large-scale Asian monsoon circulation. With the development of climate models and computer technology, numerical modeling approaches have been used to explore the role of topography in forming the Asian monsoon. Early in the mid-1970s, AGCMs were used to compare climates under conditions with and without global mountains (Manabe and Terpstra, 1974; Hahn and Manabe, 1975). Their results indicated that the QTP not only controlled the location and intensity of the Siberian High in winter, but also the establishment and development of the Asian summer monsoon. Qian et al. (1988) examined the impact of the QTP on the East Asian monsoon with a limited-area numerical model and found that atmospheric heat source anomalies related to the large-scale topography affected the development of the EASM circulation. Moreover, CCSM3 AOGCM simulations showed that the QTP has a strong effect on ocean–atmosphere interactions in the tropics and North Pacific and on atmospheric circulation and precipitation in North America, Europe, and the SH (Zhao et al., 2009; Zhou et al., 2009). Further simulations confirmed their significant impacts on the evolution of the Asian monsoon, the gradual increase in aridity in Central Asia, and the cooling of global climate through the Cenozoic (Kutzbach et al., 1989; Manabe and Broccoli, 1990; Kutzbach et al., 1993). Although there is still debate regarding the role of the QTP in the Asian monsoon system (Boos and Kuang, 2010; Wu et al., 2012), it is generally accepted that the QTP uplift increased summer heating and winter cooling on the plateau, which enhanced seasonal changes in wind directions (Ruddiman and Kutzbach, 1990), thus producing a marked increase in the intensity of the Asian summer and winter monsoons (Kutzbach et al., 1993). In recent years, Chinese scientists have conducted a number of experiments on the stepwise uplift of the QTP to further explore the role of tectonic uplift on the evolution of the Asian climate, especially on the East Asian monsoon. The key results from those experiments are now briefly described.

6.3.2. *The QTP uplift and East Asian monsoon evolution*

Due to the lack of precise and comprehensive estimates for the paleoelevation of the QTP, Liu and Yin (2002) used the COLA (Center for Ocean–Land–Atmosphere Studies) AGCM to conduct a set of experiments with ideal topography to examine the impact of stepwise uplift of the QTP on the evolution of the monsoon climate in East Asia. Eleven experiments were performed to represent the varying topography within (10°–60°N, 50°–140°E), where the height at each grid was prescribed to be 100%, 90%, . . . , 10% of the present elevation. A no-topography experiment was also performed for reference. Except for the QTP topography, all other boundary conditions remained the same as the control experiment, i.e., current conditions.

The QTP uplift caused significant changes in atmospheric circulation. In particular, the uplift was closely associated with the establishment and evolution of the Asian monsoon system. The response of the East Asian monsoon was more sensitive to the uplift than that of South Asia. Moreover, the effect of the uplift on winter monsoon was more prominent than that on summer monsoon in East Asia. In northern East Asia, the formation of monsoon climate was marked mainly by the establishment of a winter monsoon and the appearance of an alternation between dominant surface winds with opposite directions in winter and summer, which corresponded to the QTP uplift when the height reached approximately half of its current elevation. However, the monsoon was established much earlier and displayed a non-linear response in southern East Asia. Its existence was found well before the QTP reached half of its current height. Additionally, the uplift of the northern QTP mainly caused intensified summer monsoon and increased precipitation in northern East Asia, but had little influence on the South Asian monsoon (Zhang and Liu, 2010).

Given that the main uplift of the QTP occurred in a time period earlier than the Quaternary (Fort, 1996), and that pre-Quaternary boundary conditions were greatly different from the present, Jiang et al. (2008) used IAP-AGCM to perform idealized numerical experiments under the PRISM2 boundary conditions (Dowsett et al., 1999). The aim was to examine the sensitivity of the East Asian climate to the progressive uplift and expansion of the QTP under the reconstructed boundary conditions for the mid-Pliocene. When the QTP was progressively uplifted, global annual temperature declined gradually and statistically significant cooling was registered only in the NH, especially on and around the QTP, with a larger magnitude over land than over the ocean. On the contrary, annual temperature rose notably in Central Asia and most parts of Africa, as well as in northeasternmost Eurasia when the QTP exceeded half of its current elevation. Additionally, the influence of the QTP uplift on annual temperature was limited to within East Asia before half of its current elevation and then extended to most parts of the NH when the QTP continually uplifted. The QTP uplift also led to an increase in annual precipitation on the plateau but a decrease in northern Asia, the Indian Peninsula, most parts of Central Asia, part of western Asia, and the southern portion of northeastern Europe. A similar-to-present EASM system initially appeared when the QTP reached 60% of its current elevation and intensified gradually with a continued uplift. At 850 hPa, the uplift of the plateau induced an anomalous cyclonic circulation around the QTP in summer and two anomalous westerly currents respectively located to the south and north of the QTP in winter. In the mid-troposphere, a similar-to-present spatial pattern of the summer western North Pacific subtropical high was apparent only when the QTP exceeded half of its current elevation, and the East Asian trough deepened steadily in response to the progressive uplift and expansion of the QTP.

6.3.3. *Role of the QTP uplift on Asian–African aridification*

Aridification is one of the most devastating natural disasters. According to the world distribution map of arid regions developed by UNESCO (1979), the most severe and vast arid regions include northern Africa and the Eurasian interior. Identifying the primary factors involved in the formation of arid regions is undoubtedly important, both scientifically and from a practical standpoint. Geological evidence has revealed that climate developed toward conditions of aridity in inland Asia and America from the late Cenozoic (Ruddiman et al., 1989). Simulations indicate that the QTP uplift played an important role in the formation of an arid climate in the middle northern latitudes (Broccoli and Manabe, 1992; Kutzbach et al., 1993). The suggestion was that the mid-latitude aridity was largely due to orography.

To understand the impact of the QTP uplift on the development of aridity, Liu and Yin (2002) showed that, as a result of water balance linking precipitation, evaporation, runoff, and percolation, soil moisture was superior to precipitation in indicating aridity changes. As such, the most prominent feature in the calculated percentage changes of annual soil moisture between the different stages was the gradual aridity in the extensive area from Central Asia to Northwest China, and even in North Africa. Moreover, the process of desiccation in these regions intensified dramatically during the later stages of the QTP uplift.

Although simulations indicate that the QTP uplift led to the aridity of Central Asia and northern Africa, it cannot totally account for the formation of the arid regions from North Africa to Central Asia. In the distribution of annual precipitation during the course of the QTP uplift, there was a large non-mountainous rainy region, with more than 8 mm d^{-1}, from India to East Asia south of 22°N, which implies that this tropical monsoon precipitation essentially did not depend on the QTP (Liu et al., 2001). Moreover, the continental interior of northern Africa through to Eurasia, around 25°–45°N, still remained arid to a considerable degree even without the QTP. Therefore, the occurrence of arid regions and aridity in Central Asia and northern Africa should not be solely attributed to the QTP uplift.

6.3.4. *Modulation of tectonic uplift on orbital-scale EASM variability*

Geological records and numerical simulations have shown that the Asian monsoon climate variability on the geological scale is modulated by both the Earth's orbital changes and tectonic uplift of the QTP. Moreover, it is suggested that the response of the South Asian monsoon to orbital forcing could depend upon the elevation of the QTP (Prell and Kutzbach, 1997). To explore the role of the QTP uplift in modulating the response of the EASM to orbital forcing, Liu et al. (2003a) performed a set of experiments with the CCSM AGCM. Under scenarios of current mountains and non-mountainous conditions, they examined the response of the EASM to changes in precession and obliquity parameters. With the present orography, summer monsoon in northern East Asia responded significantly to orbital forcing. In the absence of the QTP, however, the orbital-scale variability of Asian monsoon reduced markedly. By examining the spatial and temporal variations of climate variables and indices, including surface and upper-air winds, air humidity and soil moisture, precipitation, and monsoon intensity, Liu et al. (2003a) suggested that the QTP may serve as an amplifier of orbital-scale variability of the EASM.

6.3.5. *Inter-model and model–data comparisons*

Results from recent studies in China further confirm those drawn from earlier simulations with respect to the influence of the QTP on the Asian monsoon, including the development of the Siberian–Mongolian high in winter (Manabe and Terpstra, 1974) and the aridity of Central Asia in summer (Broccoli and Manabe, 1992; Kutzbach et al., 1993) during the course of the uplift. On the contrary to previous studies (Hahn and Manabe, 1975; Kutzbach et al., 1993), Liu and Yin (2002) indicated that the response of the Indian monsoon to the QTP uplift was not as strong as that of the East Asian monsoon. They emphasized that the monsoon phenomenon featured the alteration of the prevailing winds with almost opposite directions between winter and summer. Therefore, wind difference between winter and summer was considered as the prerequisite for monsoon. Their results suggested that the seasonal contrast of winds, precipitation, and temperature between winter and summer did not change much in South Asia during the whole course of the QTP uplift. Even under no-topography conditions, the South Asian monsoon was clearly visible in the simulations. This conformed to the results of numerical experiments by DeMenocal and Rind (1993) and Ramstein et al. (1997), suggesting that there existed monsoonal rain areas south of 30°N even without the QTP, although the precipitation amount was lower than current levels. In this sense, the formation of the South Asian monsoon was less dependent on the existence of the QTP than the East Asian monsoon.

Due to limitations in computing resources and available geological boundary conditions, only sensitivity experiments have been performed in this field to date. It is therefore difficult to compare model results directly to geological records, and only some trends of simulated climate change in Asia could be supported by geological evidence. For example, Liu et al. (2003a) reported that the QTP uplift could amplify the orbital-scale variability of the EASM, which was in good agreement with geological records. The magnetic susceptibility of loess and red clay on the Chinese Loess Plateau also showed that the precession and obliquity components of monsoon intensity enhanced significantly during the late Pliocene (Liu et al., 2003a). At the same time, geological evidence has shown that the QTP uplifted rapidly and extended northward and northeastward considerably during 3.6–2.6 Ma BP (Li et al., 1997; An et al., 2001). Combining this geological evidence with simulations, we believe that the significant intensification of the orbital-scale EASM variability at both precession and obliquity periods is, at least partially, attributable to the strong growth of the QTP.

It is particularly noteworthy that when the QTP rose to about half of its current height, abrupt changes occurred in the evolution of the northern East Asian monsoon, e.g. the establishment of the northerly winter monsoon and the intermittent strengthening of the summer monsoon (Liu and Yin, 2002; Jiang et al., 2008). This seems to imply that there was a critical height of the QTP for its influence on the northern East Asian monsoon. On the other hand, geological evidence from both South Asia (Ruddiman et al., 1989; Molnar, 1997) and East Asia (An et al., 1999) shows some abrupt changes in the monsoons on the tectonic scale. The abrupt establishment of the northern East Asia monsoon could correspond to the events of loess deposition in the Loess Plateau in North China (Guo et al., 2002). These agreements in the change trend between simulations and geological evidence may reflect the important role of the QTP in determining regional climate evolution in East Asia. However, to comprehensively understand the mechanisms behind East Asian monsoon evolution, it is necessary to clarify the geological history of the QTP uplift, collect more geological records, and then to conduct further numerical experiments in the future.

6.3.6. *Perspective*

At present, the history of the QTP uplift is still an open question. A lack of knowledge regarding the three-dimensional paleoelevation of the QTP restricts the design of numerical experiments and comparisons with geological records. In this case, only idealized experiments, where the QTP topography is usually prescribed as some percentage of current elevation, have been designed in order to assess the effect of the QTP uplift. Although such a simplified design helps to isolate the impact of topography from those of other forcings, the actual process of the QTP uplift is more intricate, which might give rise to quite different climatic consequences. With realistic geometry of topography, more reasonable schemes should be taken in future simulations to better assess climatic response to tectonic uplift. Recently, for example, Zhang et al. (2012a) conducted numerical experiments to indicate that the uplifts of the different subregions of the QTP had different effects on the Asian climate.

The evolution of the Asian monsoon and arid climate is also associated with other forcings besides the QTP uplift. From the early Pliocene to late Miocene, other significant changes occurred in the paleogeographical environment of the Eurasian continent apart from the QTP uplift. Therefore, the reconstruction of various boundary conditions, such as vegetation, ice sheet, and atmospheric CO_2 concentrations, are also desirable for climate modeling of geological periods.

Physically-based climate models describing various feedback mechanisms are needed in the future. The absence of an interactive ocean is a limitation in previous simulations of the effect of the QTP uplift. Previously, AOGCM experiments have been performed to explore the effect of progressive mountain uplift on the Asian climate (Abe et al., 2003; Kitoh, 2004). In addition, snow–ice feedback on the QTP (Bush, 2000) and uplift–weathering feedback (Raymo and Ruddiman, 1992) may further reinforce the thermal and dynamic influence of mountain uplift. Collectively, with the continuous improvement in the reconstruction of three-dimensional paleoelevation of the QTP, and the development of climate models, we will be able to obtain a more comprehensive understanding of the tectonic–climate link through climate modeling.

6.4. ***East Asian climate transition through the Cenozoic***

6.4.1. *Evolution of the East Asian climate pattern in the Cenozoic*

At present, China is dominated by the East Asian monsoon climate. Winter northerly winds bring cold and dry air from the high latitudes of the Eurasian continent, and summer southerly winds bring warm and moist air from the tropical oceans. A large area of desert is distributed across Central Asia. However, the monsoon-dominant climate did not form until the Paleogene/Neogene boundary, also known as the Oligocene/Miocene boundary. In the Paleogene, East Asia featured a zonal climate pattern with an arid band extending from the eastern coast of China to Central Asia (e.g., Sun and Wang, 2005; Zhang and Guo, 2005; Guo et al., 2008), but in the Neogene a non-zonal climate pattern with inland aridity dominated East Asia (Zhang et al., 2007a, 2007b; Guo et al., 2008). Dating of loess-paleosol sequences and more detailed reconstructions of geological indicators have demonstrated that this major reorganization of the climate pattern occurred near the Oligocene/Miocene boundary, by *ca.* 22 Ma BP (Guo et al., 2002; Zhang and Guo, 2005; Guo et al., 2008).

6.4.2. *Impact of the QTP uplift and the Tethys retreat on climate*

The mechanisms involved in monsoon climate have received broad attention from scholars for a long time. Classical theory emphasized that the land–sea thermal contrast was the key element to monsoon (Halley, 1686). A later theory invoked the seasonal movement of planetary wind as the main cause of monsoon (Flöhn, 1956). However, those two theories cannot fully explain the formation of the East Asian monsoon because the East Asian monsoon is a complex of tropical and subtropical monsoons. Subsequently, a number of numerical experiments have focused on the impact of the Himalayan–Tibetan Plateau uplift on the intensification of the Asian monsoon and Asian inland aridity (Manabe and Terpstra, 1974; An et al., 2001; Liu and Yin, 2002; Jiang et al., 2008). On the other hand, several studies have emphasized the important role played by the Tethys retreat (Ramstein et al., 1997; Fluteau et al., 1999).

In this area, Zhang et al. (2007a) attempted to distinguish between the effects of those two major factors by using IAP-AGCM. Thirty numerical experiments were performed under six Tethys Sea and five Himalayan–Tibetan Plateau conditions. In the five Himalayan–Tibetan Plateau conditions, the maximum height of the plateau was progressively increased from 1500 m to 4500 m. In the six Tethys Sea conditions, the sea was gradually closed from a large sea with a full connection to the Arctic to a small epicontinental sea. Other boundary conditions were kept constant throughout the experiments.

This set of experiments confirmed again that the Himalayan–Tibetan Plateau uplift can strengthen the East Asian monsoon. The uplift remarkably increased the seasonal contrast of precipitation in the monsoon areas and Northwest China. Furthermore, the experiments illustrated details about the impact of the Tethys retreat on the East Asian climate. Two kinds of precipitation fields were obtained in East Asia. One was a zonal pattern, while the other was non-zonal one. For the former, a deficient rain belt with precipitation less than 1.5 mm d^{-1} was distributed from the eastern coast of China to Central Asia. In the non-zonal pattern, a deficient rain region only appeared in Central Asia. Thus, the simulated transition of precipitation patterns agreed well with the reorganization of climate suggested by geological records. The transition occurred when the Tethys retreated from the southern part of West Siberia to the Turan Plate. The retreat at this stage led to the reorganization of the pressure system by a changing land–sea thermal contrast. In summer, a low pressure anomaly was centered on the Turan Plate and Northwest China, where the sea was changed into land. The low pressure anomaly caused a cyclonic circulation anomaly in East Asia. Along the southeastern edge of the anomalous cyclonic circulation, the southwesterly winds strengthened greatly. They carried a larger amount of water vapor and increased precipitation in the monsoon areas. In winter, the retreat led to a high pressure anomaly in Northwest China and a low pressure centered on Mongolia. As a result, northwesterly winds intensified, and it reduced precipitation and increased aridity in inland China.

6.4.3. *Impact of the South China Sea expansion on climate*

IAP-AGCM was also used to examine the potential effects of other tectonic changes (Zhang et al., 2007b). Additional factors addressed were the Indian Peninsular drift, the South China Sea expansion, and the East China Sea transgression. The experiments revealed a relatively subordinate role of the Indian Peninsular drift and the East China Sea transgression. The South China Sea expansion, however, was another major forcing, in addition to the important roles of the Tethys retreat and the Himalayan–Tibetan Plateau uplift. The expansion provided sufficient water vapor for summer precipitation in the monsoon areas, and then enhanced the humidity contrast between East Asia and Central Asia.

These simulations demonstrated again that the geographical evolution drove the reorganization of the climate pattern over China during the Cenozoic. The Tethys retreat and the Himalayan–Tibetan Plateau uplift strengthened the East Asian monsoon to provide the dynamic conditions, while the South China Sea expansion provided sufficient water conditions for the major reorganization of the climate pattern in East Asia. These three factors acted together to cause the major reorganization of regional climate in East Asia.

6.4.4. *Perspective*

The above-discussed studies were still limited by the coarse horizontal resolution of IAP-AGCM and prescribed SSTs and sea ice extent. A new set of simulations of a high resolution AGCM also showed that East Asia was dominated by a zonal desert/steppe climate in the Eocene (Zhang et al., 2012b), supporting the results described above. The coarse resolution of IAP-AGCM hence has less effect on simulations of basic climate patterns in East Asia. In future simulations, the effect of an interactive ocean should be emphasized. Caused by a large drop in atmospheric CO_2 concentrations and changes in oceanic circulation, the cooling event that happened at the boundary of the Oligocene and Miocene might have also played an important role in the evolution of climate in East Asia (Zhang et al., 2012b). The task remains to explore the possible relationship between the major reorganization of climate and the changes in the oceans at the boundary of the Oligocene and Miocene.

7. Conclusions and perspective

Over the last millennium, changes in solar radiation and volcanic activity were mainly responsible for pre-industrial climate change, while an increase in atmospheric greenhouse gas concentrations played the most important role in the warming of the 20th century over China. Although simulations agree in several respects with reconstructions, model–data discrepancies are still notable in China (e.g., Liu et al., 2005; Peng et al., 2009; Man et al., 2012; Man and Zhou, 2014). To reduce the uncertainties surrounding simulations, the potential effect of changes in atmospheric aerosols and land-use and land-cover needs to be further evaluated in future work. Historical climate simulations derived from a hierarchy of climate models should be compared so as to investigate their common and different responses to the same or similar forcings at the regional scale. The physical processes that affect the sensitivity of climate models to the specified natural/anthropogenic forcing agents should also be explored.

Changes in the Earth's orbital parameters were the principal cause for mid-Holocene climate change. However, simulations with this forcing disagree in temperature with proxy data over China, particularly for winter. It is worth emphasizing that an interactive ocean appears to amplify the response of climate models to mid-Holocene orbital forcing and reduce model–data disagreements over China, although the underlying mechanism remains unclear (Wei and Wang, 2004; Jiang et al., 2012). Reconstructed vegetation appears to be an important component for mid-Holocene East Asian climate in AGCM experiments (Wang, 1999a, 2002; Chen et al., 2002), whereas interactive vegetation has little overall effect on the climate of China based on coupled models with a dynamic vegetation model (Jiang et al., 2012; Tian and Jiang, 2013). In this regard, both vegetation reconstruction and climate–vegetation interaction require further study. The mid-Holocene annual and winter temperature changes over China from multiple proxy data are opposite to those from 36 PMIP models (Jiang et al., 2012). More reconstructions and simulations are urgently needed to investigate whether such mismatch arises from the models, from the proxy data, or from both sides. In addition, more attention should be given to both transient simulations for the whole Holocene and time-slice simulations for climate events, such as those that occurred at 8.2 and 4 ka BP, so as to enhance our knowledge of the nature and cause of Holocene climate change.

In response to the larger ice sheets of the NH in the LGM, more extensive sea ice, colder SSTs, and lower atmospheric CO_2 concentrations, a number of experiments have reliably reproduced the main features of the glacial climate over China. However, the simulated changes are weaker overall than those suggested by proxy data (Jiang et al., 2011). A series of sensitivity experiments suggested that the effect of reconstructed vegetation, the impact of reconstructed SSTs in the western Pacific, and the potential influence of the QTP environment change were all remarkable (Chen et al., 2000; Yu et al., 2001; Liu et al., 2002a; Jiang et al., 2003; Yu et al., 2003a; Zhao et al., 2003; Jiang et al., 2004; Zhao et al., 2004; Sui and Zhao, 2005). Climate change due to those factors can partly reduce model–data disagreements over China, particularly on the QTP. In this sense, it is necessary to systematically evaluate the effect of an interactive ocean and vegetation, the impact of different SST reconstructions in key regions, and the environmental conditions on the QTP and their climatic consequences for the East Asian monsoon region in future simulations. Additionally, to what extent the latest PMIP3 simulations are consistent with earlier simulations and proxy data should be evaluated, which will be helpful in understanding the LGM East Asian climate.

Orbitally induced insolation changes are hypothesized to be responsible for the climate change in China during the late MIS3 (Shi et al., 2001; Shi and Yu, 2003). Preliminary experiments have revealed that the glaciations in the NH and vegetation change can modify climate model response to orbital forcing, and therefore also contribute significantly to the late MIS3 climate in China (Yu et al., 2003b, 2005, 2007). Although part of the simulated late MIS3 climate is supported by reconstructions, model–data disagreements are still not settled over the country. To what extent the obtained results are model-dependent and how ocean feedback behaves need to be specifically investigated.

Preliminary simulations have revealed basic characteristics of the mid-Pliocene global climate (Chandler et al., 1994; Sloan et al., 1996; Haywood et al., 2000; Jiang et al., 2005). The spatial pattern of the mid-Pliocene climate and the underlying mechanism, however, are highly unclear (Jansen et al., 2007). Over China, model–data disagreements in changes of precipitation and the EASM need to be further addressed (Jiang, 2009; Zhang et al., 2013b). Of particular interest is to employ state-of-the-art climate models to simulate the mid-Pliocene climate, which will improve our understanding of a warmer-than-present climate regime. During the Cenozoic, the QTP uplift was one of the most important events on Earth. Although the spatial and temporal evolution of the QTP remains unresolved, a series of idealized numerical experiments consistently revealed that the progressive uplift and expansion of the QTP played important roles in forming the modern Asian climate, particularly for the East Asian monsoon climate (Liu and Yin, 2002; Jiang et al., 2008; Zhang and Liu, 2010; Zhang et al., 2012a). In addition, the Tethys Sea retreat and the South China Sea expansion could have had important effects on the formation of the East Asian monsoon-dominant environment pattern during the late Cenozoic (Zhang et al., 2007a, 2007b, 2012b).

Finally, we would like to stress that a wealth of historical and geological data have been used to reconstruct past climate change over China, e.g., historical documents, tree rings, stalagmites, lacustrine and fluvial sediments, marine sediments, ice cores, loess and red clays, paleosols, and pollen data. It is promising to employ climate and Earth system models to simulate past climate change and events in the East Asian monsoon region, and to compare simulations with reconstructions. The application of regional climate models should be helpful when model–data comparisons are performed at the regional scale. All of these studies will provide insights into the dynamic mechanisms of climate change on a range of timescales. Interdisciplinary cooperation will undoubtedly advance our knowledge of past, present, and future climate change in China, which comprises $\sim 25\%$ of the world's population.

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