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Evolution of the monsoon and dry climate in East Asia during late Cenozoic: A review

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Climate in Eastern Asia is composed of monsoon climate in the east, arid and semi-arid climate in the north and west, and the cold and dry climate of Qinghai-Tibetan Plateau in the southwest. The underlying causes for the evolution of East Asian climate during late Cenozoic have long been investigated and debated, particularly with regards to the role played by the Qinghai-Tibetan Plateau uplift and the global cooling. In this paper, we reviewed major research developments in this area, and summarized the important results. Based on a synthesis of data, we propose that the Qinghai-Tibetan Plateau uplift alone cannot fully explain the formation of monsoon and arid climates in Eastern Asia during the past 22–25 Ma. Other factors such as the global ice volume and high-latitude temperature changes have also played a vital role. Moreover, atmospheric CO_2 changes may have modulated the monsoon and dry climate changes by affecting the location of the inter-tropical convergence zone (ITCZ), which controls the monsoon precipitation zone and the track of the East Asian winter monsoon during late Cenozoic. The integration of high-resolution geological record and numerical paleoclimate modeling could make new contributions to understanding the climate evolution and variation in eastern Asia in future studies. It could facilitate the investigation of the regional differences in East Asian environmental changes and the asynchronous nature between the uplift of Qinghai-Tibetan Plateau and their climatic effects. These would be the keys to understanding underlying driving forces for the evolution of the East Asian climate.

East Asian climate, Qinghai-Tibetan Plateau, Atmospheric CO_2, late Cenozoic, environmental evolution

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East Asian climate (EAC) consists of the monsoon climate in southeast, arid climate in northwest, and the highland climate in Qinghai-Tibetan Plateau. Evidences from both temporal and spatial investigations show that the EAC system has been established since late Cenozoic, 22–25 million years (Ma) ago (Liu et al., 1998; Guo et al., 2002, 2008; Wang et al., 2003, 2005; Qiao et al., 2006; Qiang et al., 2011; Miao et al., 2012; Liu and Dong, 2013). The uplift and growth of the Qinghai-Tibetan Plateau and the global cooling are considered as the two most important drivers in the EAC evolution during late Cenozoic. Recently, the roles played by insolation, ocean current and land surface processes in the EAC evolution are also investigated. Understanding the EAC evolutionary processes and their underlying driving mechanisms is at the frontier of paleoclimate science. In addition, this understanding is important for projecting future EAC changes and evaluating their socio-economic impacts. This is of particular importance because Asia is the most populous region with the fastest economic development in the world, where climatic changes will lead to profound impacts. To date, important ques-

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*Corresponding author (email: huayulu@nju.edu.cn) tions regarding the EAC evolution and the driving mechanisms are yet to be answered. In this paper, we reviewed recent developments and synthesized the data in this research area in order to provide new insights in the origin, evolution and variability of the EAC. In particular, we analyzed the origin and evolution of the monsoon and dry climate during late Cenozoic, and the roles played by the global cooling and Qinghai-Tibetan uplift on East Asian climatic changes.

1 Evolution of East Asian climate and Qinghai-Tibetan Plateau during late Cenozoic

1.1 Evolution of the arid climate in East Asia

Climate in north and west parts of Eastern Asia is extremely dry. The land is exposed to strong physical weathering processes, which produce large amount of silty sediments that are carried out of this region by wind, making this region a very important dust source. The silt dust is transported by the Eastern Asian winter monsoon (part of the Eastern Asian monsoon system, the other part being the Eastern Asian summer monsoon) and the westerly jet to leeward region, forming the huge aeolian silt deposit in Chinese Loess Plateau (Liu, 1985), and to even as far as the northern Pacific Ocean (Duce et al., 1980), Greenland and North America (Biscaye et al., 1997; Yu et al., 2013). These aeolian silt deposition sequences are excellent archives of past atmospheric circulation and the climate changes.

Chinese loess deposition provides a wealth of information for the dry climate evolution in the past 2.5 Ma (Liu et al., 1985; An et al., 1990; Ding et al., 1994; Guo et al., 1998). Additional studies show that the Red Clay formation underlying the thick Quaternary loess deposit in northern China also has eolian origin and were formed from ~8 to 2.5 Ma (Zhao, 1989; Sun et al., 1997; Ding et al., 1998; Qiang et al., 2001; Lu et al., 2001; Guo et al., 2004). A breakthrough came about when the aeolian silt deposit was discovered in Qin’an, Gansu Province, northern China. It is shown that the aeolian sediments were formed ~22 Ma ago, which suggests that the arid climate in West and North Eastern Asia was already established by that time (Guo et al., 2002, 2008; Qiao et al., 2006; Hao et al., 2008). Later studies confirm this aeolian silt deposit mantled an extensive area in northern China (Lu et al., 2004a; Wen et al., 2005; Sun et al., 2010), not just limited to Qin’an area. This provides more evidence that the arid climate, similar with the modern arid climate, was first established between 22–25 Ma. Before this time, the arid climate in Eastern Asia was distributed along a latitudinal climatic zone, controlled by the distribution of planetary insolation. After 22–25 Ma, the latitudinal climatic zone was broken, the monsoon climate replaced the arid climate in Eastern Asia (Liu et al., 1998; Wang et al., 2005; Sun and Wang, 2005; Guo et al., 2002, 2008; Guo, 2010). The stepwise drying of the arid climate is revealed by the aeolian silt loess and Red Clay deposit, with significant episodes of rapid climate drying occurred at ~14, ~8, ~ 3.6, ~2.5 and 1.2–0.9 Ma respectively (Qiao et al., 2006; Lu et al., 2010; Zeng et al., 2011) (Figure 1). At the orbital timescale, these sedimentary sequences recorded the strong cyclical wet-dry climate changes with periods of ~20, ~40 and ~100 ka, supporting the idea that the insolation variations which modulated glacial/interglacial changes probably also controlled the wet-dry changes in the arid climate in Eastern Asia.

The wealth of depositional sequences in many basins of Eastern Asia also provided important records of the arid climate evolution. The paleoclimatic records from Tarim Basin and the surrounding area revealed that the arid climate was formed at least at ~24 Ma, and was further strengthened at ~7.0 and 4.0–2.0 Ma respectively (Zheng et al., 2000; Sun et al., 2010; Tang et al., 2011). The pollen and other records from Xining Basin indicated that the arid climate appeared at the time of transition between the Eocene and Oligocene, and, was strengthened at ~14, ~7.0 and ~2.0 Ma (Lu et al., 2004a; Dupont-Nivet et al., 2008; Xiao et al., 2010; Long et al., 2011; Wang et al., 2012). Pollen, grain-size and oxygen stable isotopic composition of the sediments from Linxia Basin show that the arid climate was intensified during distinct episodes at ~22, 14–12, 8–6.5 and ~2 Ma (Ma et al., 1998; Li and Fang, 1998; Wang et al., 1999; Dettman et al., 2003; Wang and Deng, 2005). Pollen, oxygen and carbon isotopic composition, and mammalian fossils from Guanzhong Basin demonstrated that the arid climate was enhanced at ~11, ~7, ~2.5 and ~1.0 Ma respectively (Fortelius et al., 2002; Kaakinen et al., 2006; Liu et al., 2009). High-resolution records from paleomanetic stratigraphy and pollen analysis show that the arid climate was strengthened at ~20, ~14 and ~1.0 Ma, the investigators suggested that these episodes of drying were caused by the stepwise global cooling (Jiang et al., 2008a, 2008b). Moreover, the orbital timescale periodicities coincided with these climate shifts which are strongly coupled with the global ice volume/temperature variations (Lu et al., 2004b, 2009). A recent quantitative reconstruction of the temperature change from the last glacial maximum to the Holocene Optimum shows a 6–14°C changes in North China (Yu et al., 2013). This is close to the temperature shift from the Miocene to Pleistocene (Xue et al., 2006), and may show the analogue of the two changes at the tectonic and orbital timescales.

1.2 Origin and evolution of the Asian monsoon

Many geological evidences suggest that the climate in the Paleogene (Paleocene, Eocene and Oligocene, ca. 65–24 Ma) in Asia was dominated by the latitudinal zone climate. The monsoon circulation was weak and limited in a narrow region near the ocean coast. After 22–25 Ma, the modern monsoon circulation was established (Guo et al., 2002, 2008; Guo, 2010). The strong monsoon circulation breaks the latitudinal climate zones and brought more precipitation to Eastern Asia (Guo et al., 2002, 2008; Guo, 2010). The modern arid climate in the interior Asia was formed at the same time. The arid climate in this region existed much earlier than the time of Oligocene/Miocene boundary, but it was different from the dry climate of late Cenozoic era. The arid climate before Miocene was formed by the subtropical high pressure where the sinking air led to a dry climate, whereas the arid climate after the early Miocene in north and west of Eastern Asia was formed by high topography and high-latitude cold surges.

Chinese scientists have long investigated the origin and evolution of Asian monsoon climates, including some seminal studies (Yang, 1987; Li et al., 1988; Cao et al., 1989; An et al., 1990). Many geological and paleoclimatic evidences show that the Asian monsoon was first established at the early Miocene with stepwise evolution and periodic variations during the past ~25 Ma (Liu and Ding, 1998; An et al., 2000; Lu et al., 2004b, 2009; Wang et al., 2005; Wang, 2009; Molnar et al., 2010). The East Asian winter monsoon was stepwise strengthened since the late Miocene, but the Asian summer monsoon was stronger in the Miocene and Pliocene than in the Pleistocene (Guo et al., 2002, 2008; Wang et al., 2003, 2005; Jia et al., 2003; Xue et al., 2006; Wan et al., 2007; Jiang et al., 2008a, b; Lu et al., 2010). In the Quaternary, the Asian summer monsoon went through stepwise weakening, whereas the winter monsoon was strengthened (Ding et al., 1994, 1995; Guo et al., 1998; Wang et al., 2003; Lu et al., 2004b, 2009).

1.3 Growth of Qinghai-Tibetan Plateau

Since the collision of Eurasian and Indian plates in the Paleocene-Eocene, a series of tectonic deformation and mountain building occurred in Asia, which includes the closure of Paratethys Sea and the uplifting of the Himalayas and Qinghai-Tibetan Plateau (Chen et al., 2010; Wang et al., 2011; Xu et al., 2013). Some researchers suggest that the impacts of the collision were propagated northward, thus the tectonic deformation is younger in the north than that in the south (Tapponnier et al., 2001). Therefore there exist regional difference and asynchronous growth of the mountain belts (Wang et al., 2011). It seems that there is great discrepancy in time between the mountain building in the southern and northern Qinghai-Tibetan Plateau. The southern Tibetan Plateau uplifted first, followed by the northern Qinghai-Tibetan Plateau. However, evidence shows that the central Qinghai-Tibetan Plateau has reached a significant altitude in the Eocene-Oligocene (Chung et al., 1998; Rowley and Currie, 2006; Wang et al., 2008; Zhang et al., 2008). Other observations show that the central and southern Tibetan Plateau and the Himalayan mountains reached a high altitude in middle-Miocene, ~14 Ma ago (Coleman and Hodges, 1995; Clift et al., 2006, 2008; Spicer et al., 2003; Deng et al.,

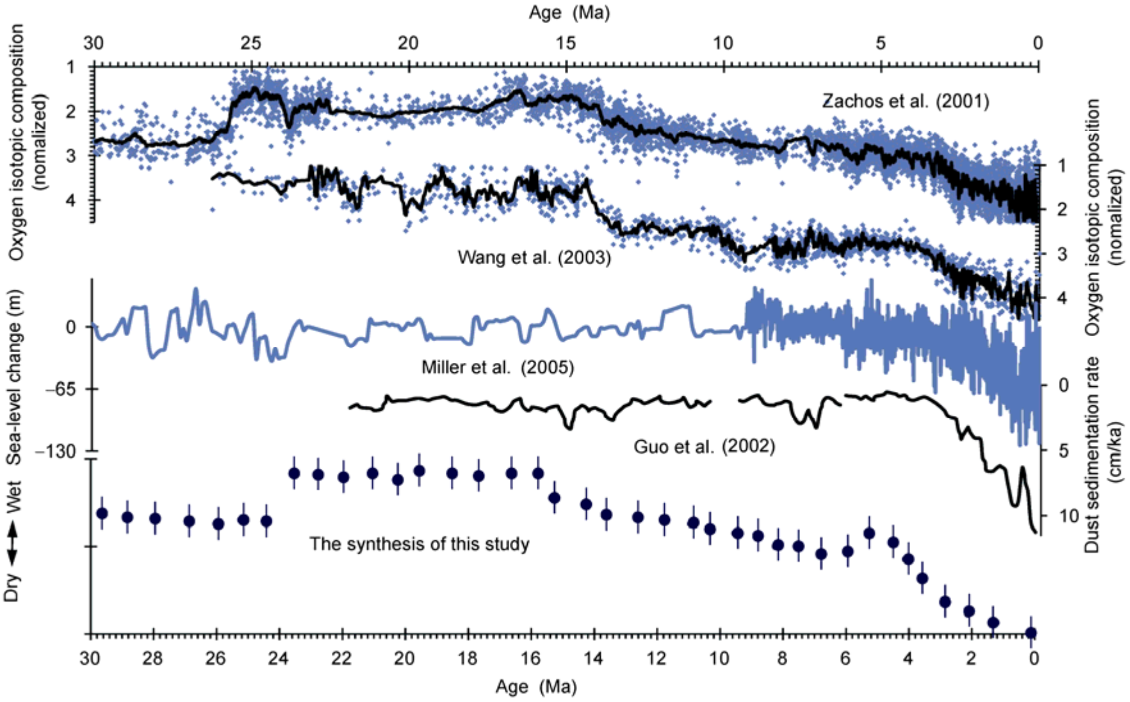

Figure 1 Evolution of the monsoon and dry climate in Eastern Asia during late Cenozoic and its possible linkage with global temperature. From top to bottom, the first curve is the global ice volume/temperature variations (Zachos et al., 2001); the second curve is the deep-sea record from South China Sea (Wang et al., 2003); the third curve is the sea-level changes (Miller et al., 1987); the fourth curve is the paleoclimate record from the loess deposit at Qin'an, central China (Guo et al., 2002); the fifth dot line shows a synthesis of the paleoclimatic changes of depositional records from Linxia Basin (Ma et al., 1998), Sikouzi sedimentary section in Ningxia (Jiang et al., 2008a, 2008b), Tarim Basin (Tang et al., 2011) and Guanzhong Basin of this study.

2011; Zhang et al., 2012). Some studies show that the Northern Qinghai-Tibetan Plateau reached a significant altitude in early to middle Miocene (Lu and Xiong, 2009; Li et al., 2011), and the commencement of the uplift can be extended back to as early as the Eocene, close to the timing of the collision between the Indian and Asian Plates (Xu et al, 2013). However, other studies show that the northern Qinghai-Tibetan Plateau significantly uplifted in the late Miocene and the Pliocene-Pleistocene, and the main uplift occurred as late as the Pleistocene (Li et al., 1979; Zhang, 1981; Li, 1999).

A synthesis study of low-temperature thermo chronology data, sedimentology and tectonic deformations reveals significant tectonic uplift and rapid mountain erosion that occurred at 60–35, 25–17, 12–8 Ma (southern Tibet 17–12 Ma) and ~5 Ma, respectively (Zhang et al., 2008, 2010; Clift et al., 2006, 2008). In addition, it seems that the rapid uplift and erosion in Qinghai-Tibetan Plateau were partially synchronous (Zhang et al., 2008, 2010; Clift et al., 2006, 2008). More recent studies suggest that the strong tectonic deformation occurred at same time with the rapid mountain building and surface erosion, and that the surface erosion was dominated by mountain building (Fang et al., 2005; Dai et al., 2005; Molnar et al., 2005, 2009). Studies on the aeolian sediment in northeastern Qinghai-Tibetan Plateau and surrounding regions suggest that the high topography and mountain-basin systems in western Chinese Loess Plateau were formed in the early Miocene (Zhan et al., 2010). There were probably some tectonic movements in this region during the Miocene to Pleistocene, but the existence of the continuous aeolian silt deposition indicates the tectonic movement had less effect on the mountain building and surface erosion since around ~22 Ma (Ge et al., 2012). Many newly obtained evidences show that the main tectonic movements in Qinghai-Tibetan Plateau occurred at the early to middle Miocene (Zhong et al., 1996; Yin 2006; Royden et al., 2008; Molnar and Stock, 2009; Xu et al., 2013). The paleoaltitude reconstruction show the plateau reached a significant elevation during this time (Colman, 1995; Bluisik et al., 2001; Specier et al. 2003; Rowley and Currie 2006; Clift, 2006; Wang et al., 2008; Deng et al., 2011), indicating the Qinghai-Tibetan Plateau was formed before the middle Miocene. The growth after the middle Miocene was supplementary, and did not change the basic landform.

If the high topography in Qinghai-Tibetan Plateau has existed since the Paleocene and Eocene, how does this high-relief affect Asian climate? Based on existing data, the EAC was characterized by the latitudinal zonal climate before the Oligocene-Miocene boundary (Liu et al., 1998; Guo et al., 2002, 2008; Sun and Wang, 2005). This east-west extended arid climate zone was broken at the transitional time of the Oligocene and the Miocene (around 22–25 Ma), when the climate was separated into the wet monsoon climate in the east and the arid interior climate in the west Asia (Guo, 2010). Based on these observations, we suggest the monsoon and arid climate in Eastern Asia was formed in the early Miocene (~22 Ma), when the Qinghai-Tibetan Plateau reached a critical height that triggered the monsoon circulation and led to the formation of arid climate in central and north Asia. Evolution and change of the monsoon and arid climate since late Miocene were probably caused by the surface feedback and/or other factors such as the global ice volume and high-latitude temperature. The impact of uplift and growth of Qinghai-Tibetan Plateau on the EAC changes during the Pliocene and Pleistocene, especially during the late Quaternary, is quite limited.

2 Evolution of East Asian climate during late Cenozoic and its driving mechanism

2.1 Elements that influence evolution of East Asian climate

There are at least four major hypotheses on the formation and evolution of the East Asian monsoon and arid climates: (1) The high relief of Qinghai-Tibetan Plateau played an essential role in forming the monsoon and arid climate during the late Cenozoic by blocking moisture transported from the ocean to the interior Asia, enhancing the heating difference between the ocean and land, and affecting the atmospheric circulation that controlled precipitation in east Asia (Manabe and Terpstra, 1974; Kutzbach et al., 1989; Shi et al., 1998; Li, 1999; Liu and Yin, 2002; Liu and Dong, 2013). This has been the widely accepted view of the EAC evolution at the tectonic time scale. (2) There was still part of the Tethys Sea (Para-Tethys Sea) in western Asia during the Paleocene, as the complete retreat of the Tethys Sea in Asia did not happen until the late Miocene and early Pliocene. Therefore, some studies suggest that the retreat of the Tethys Sea probably played a similar role in forming the monsoon climate as that of the Qinghai-Tibetan Plateau uplifting and growth (Ramstein et al., 1997; Zhang et al., 2007a, 2007b). (3) Additional observations and modeling results suggest that the Himalayans alone rather than the Qinghai-Tibetan Plateau as a whole caused a strong monsoon circulation by separating warm moist air over the Indian subcontinent from the cold and dry air from the extratropics (Boos and Kuang, 2010; Molnar et al., 2010). 4) Integrated studies show that the global cooling during the late Cenozoic had significant influences on driving the Asian monsoon climate and the Asian interior arid climate (Chen, 1991; Li et al., 2006; Lu et al. 2010). In particular, the global cooling might have played a more important role since the late Miocene, as the strong coupling of the climate evolution in East Asia and the global cooling in Quaternary might suggest a close link between the two.

However, none of the above mentioned hypotheses by itself can fully explain the EAC evolution during late Cenozoic. There is still much disagreement on the timing and amplitude of Qinghai-Tibetan Plateau uplift and growth.

Therefore, any model that tries to simulate the impact of the Qinghai-Tibetan Plateau uplift on the climate should be reexamined. A direct link between the Qinghai-Tibetan uplift and the EAC evolution remains highly speculative. For instance, the Asian monsoon precipitation was stronger in the Miocene and Pliocene than that during the Pleistocene (Xue et al., 2006). This is very difficult to explain by the plateau uplift, because this hypothesis (Kutzbach et al., 1989; Li and Fang, 1998; Li, 1999; An et al., 2001) suggests that the uplifting of the Qinghai-Tibetan Plateau strengthened the summer monsoon circulation, and therefore there should have more precipitation in eastern Asia during the Pleistocene, but this conflicts with existing geological evidence (Figure 2).

We emphasize the importance of the global cooling forcing on the EAC evolution during the late Cenozoic mainly based on the strong correlation between the two since ~15 Ma, particularly since ~8.0 Ma. For instance, the rapid expansion of ice cover in Antarctic at ~14 Ma can be linked with the drying shift occurred at this time (Chen, 1991; Jiang et al., 2008a, 2008b; Lu et al., 2010); the dry climate and monsoon changes at ~8.0, ~3.6, 2.5 and 1.2 Ma coincided with the global ice volume/temperature shifts occurred at these times (Shackleton et al., 1984; Zachos et al., 2001). On the other hand, the evidences such as river terrace, tree line migration and climatic change that support the plateau uplift during late Pliocene and Pleistocene are equivocal, leading the conclusion that plateau uplift drove the EAC shifts since ~3.6 Ma is untenable. Moreover, it is clear that the global cooling caused weakening of moisture

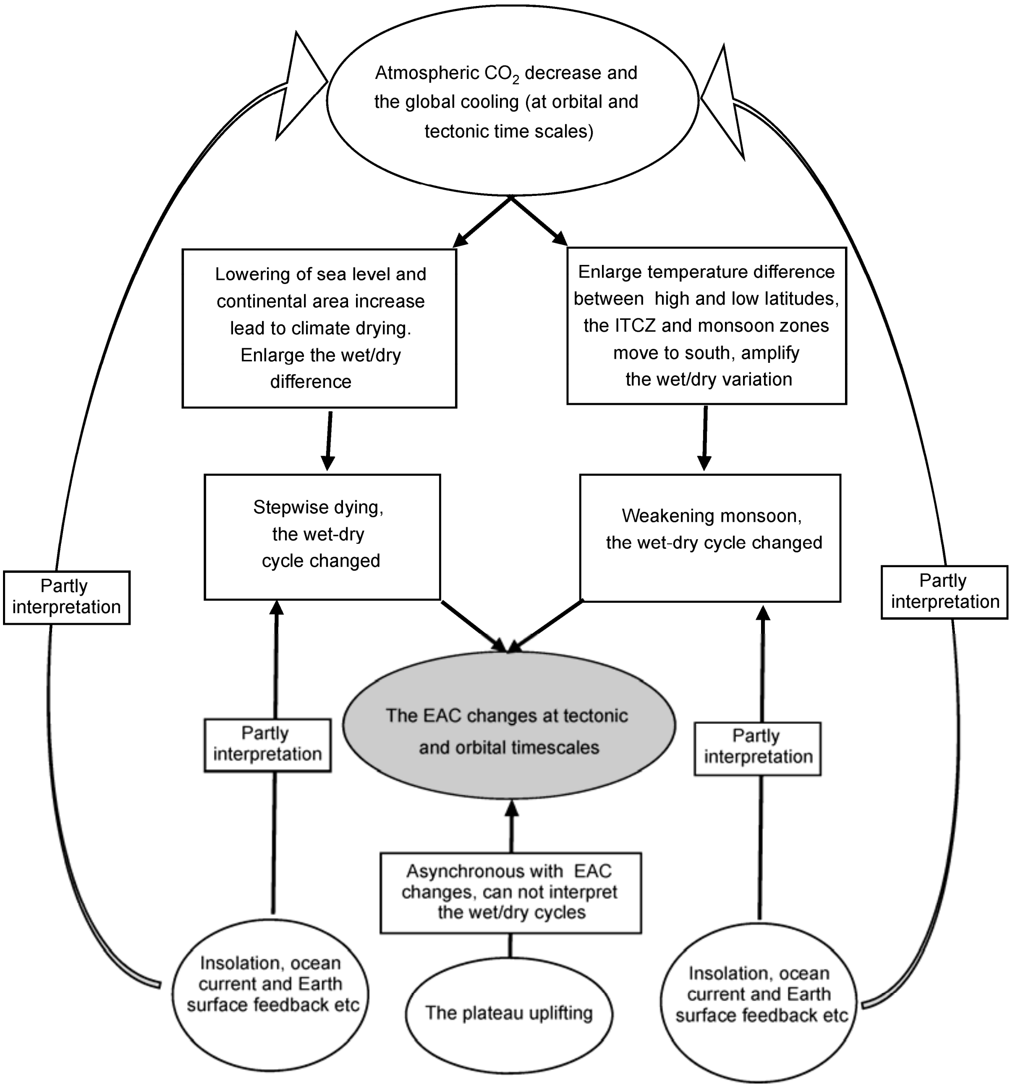

Figure 2 A conceptual model of factors that influenced the East Asian climate changes during late Cenozoic. The shaded ellipse represents the paleoclimatic records of the past ~22 Ma, which is coupled with the ice volume/CO_2 variations, but not well coupled with the insolation, ocean current (less data), tectonics and the Earth surface process. This model shows that the global temperature/CO_2 variations are the most important and direct forcing of the EAC changes at tectonic and orbital timescale during late Cenozoic. The insolation, ocean current, tectonic movement and Earth surface process play partial roles in forcing the paleoclimatic changes but not the direct drivers.

transport, lowering of sea level and increase of continental surface, all of which would lead to drying of East Asia (Figure 2). This relationship also existed at the orbital timescale (Liu and Ding, 1993, 1998). The uplift forcing hypothesis can not explain the EAC drying during late Cenozoic, because the growth and uplift of Qinghai-Tibetan Plateau would enhance the Asian summer monsoon circulation, causing EAC to become wetter, which is not what has been observed. In conclusion, the basic topography and landform of Qinghai-Tibetan Plateau was established at early Miocene, with the formation the EAC system. The evolution of EAC after the early Miocene was largely driven by the global cooling rather than the plateau growth.

2.2 Closure of Tethys Sea, Himalayan insulation and global cooling on EAC

Some geological data and numerical modeling seem to support the idea that the Tethys Sea closure caused the EAC changes during late Cenozoic (Ramstein et al., 1997; Zhang et al., 2007a, 2007b). However, suggested timing for the retreat of the Tethys Sea from western China varied from Oligocene to late Pliocene (Sun et al., 2011; Sun and Jiang, 2013). Thus the modeling results have not been directly tested by geological data. To complicate the matter even more, the tectonic uplift of the Qinghai-Tibetan Plateau was probably synchronous with the retreat of the Tethys Sea, because both were driven by the collision and extrusion of the Indian and Eurasian plates. Therefore, separating the roles of the Tethys Sea closing and the Qinghai-Tibetan Plateau growth on the EAC is still very difficult.

The insulation effect of the Himalayan Mountains alone may trigger the Indian monsoon circulation (Boos and Kuang, 2010), but this conceptual model cannot explain the evolution of the Eastern Asia monsoon climate. Some suggest that the East Asian monsoon is not a typical monsoon climate because of the lack of high topography, such as the Himalayas in Eastern Asia (Molnar et al., 2010). New high-resolution modeling results do not support the idea that the Himalayan insulation alone can trigger the Asian monsoon circulation (Wu et al., 2012). The heating of the Qinghai-Tibetan Plateau is still necessary to maintain the Asia monsoon circulation (Wu et al., 2012). Some modeling research also considered the regional difference and asynchronous growth of the plateau, and reached the same conclusion that the Himalayans alone could not trigger the monsoon circulation (Zhang et al., 2012; Liu and Dong, 1993), but these hypotheses are hotly debated (Qiu, 2013).

As a result, the global cooling might provide the best explanation for the formation of the monsoon and arid climate in East Asia during late Cenozoic (Figure 1). There were significant stepwise and periodical changes of the global ice volume, temperature and sea-level during late Cenozoic (Zachos et al., 2001; Wang et al., 2005). These changes were synchronous with that of the EAC evolution during late Cenozoic, indicating a possible causal link between the two (Lu et al., 2010). Geological records from East Asia (Wang et al., 2003, 2005; Lu et al., 2010) suggest synchronicity between the global cooling and monsoon/arid climate evolution.

On the basis of the above analyses, it seems the global cooling forcing hypothesis may best explain the dry climate and monsoon evolution during late Cenozoic in east Asia. It is clear that the global cooling has strengthened the Siberia High (which dominates winter monsoon circulation and aridity in East Asia) (Figure 2), hence driven the EAC system evolution. At the same time, the cold climate reduced the moisture transportation by the Asia monsoon circulation, hence caused a dry East Asia. Other studies also support this interpretation (Garzione et al., 2010). However, there were periods of decoupling between the global cooling and the monsoon precipitation reduction. For example, precipitation was the highest in the early Miocene (Clift et al., 2006), but the oxygen isotopic composition of deep-sea sediment (Zachos et al., 2001) shows that the temperature at this time was not higher than that of the middle Miocene and the early Pliocene. In addition, the monsoon precipitation at the two thermal maxima in the early middle Miocene and early Pliocene during the past ~24 Ma was not the highest. These disagreements with the model results require further investigation.

2.3 Role of atmospheric CO_2 on the EAC evolution

Atmospheric CO_2 variation affects the global temperature in general, but disagreements exist on whether the CO_2 changes were leading or lagging behind the global temperature during late Cenozoic (Sigman and Boyle, 2000; Shakun et al., 2012; Guo et al., 2012; Parrenin et al., 2013). Furthermore, the specific forcing mechanism is not clear. Many observations show that the atmospheric CO_2 and other greenhouse gases have varied with global temperature during late Cenozoic (Vincent and Berger, 1985; Jouzel et al., 2007; Tripati et al., 2009). There are two linkages between the atmospheric CO_2 and the EAC during late Cenozoic. (1) The uplift and the increased weathering of Qinghai-Tibetan Plateau can draw down more atmospheric CO_2 and cool the Earth (Raymo and Ruddiman, 1992). Recent investigations show that CO_2 uptake of the Qinghai-Tibetan Plateau alone cannot explain the Earth's cooling during the late Cenozoic (Willenbring et al., 2010; Li and Elderfield, 2013). (2) The change of atmospheric CO_2 cooled the Earth, shifting the ITCZ southward, thus reducing the monsoon precipitation (Lu et al., 2013), as discussed in the previous section of this paper. This conceptual model has yet to be fully tested. However, when we investigate the paleoclimate change during the late Cenozoic, the role of atmospheric CO_2 must be considered.

The monsoon precipitation belt is strongly associated with the ITCZ location (Wang, 2009; Lu et al., 2013). When the Earth cooled, it pushed the ITCZ towards the tropical region, hence changed the location of the monsoon precipitation belt and reduced the monsoon precipitation in East Asia. Our recent studies on the geological record and numerical modeling (Lu et al., 2013) show that the cooling could alter the rainfall patterns during at least the past 21 ka. However, the short length of the geological record limits its ability to test the long-term impacts of the global cooling on the East Asian monsoon patterns.

We suggest that there exists an atmospheric circulation link between the global temperature and eastern Asian climate, but this hypothesis requires further testing through numerical modeling. The temperature of high latitude region, the ITCZ location and East Asian monsoon precipitation should all be linked by the atmospheric circulation, and the global climate change modulated the EAC evolution at tectonic time scale. Underlying causes for the global cooling during late Cenozoic are beyond the scope of this paper, and no satisfying answers exist at this stage. The global climate was affected by a wide array of important factors, such as the formation of Antarctica circumpolar current, ocean current changes, atmospheric CO_2, tectonic uplift and weathering and insolation changes etc. Therefore, there is still much work to be done in order to understand the roles played by these factors on the Asian climate during the Cenozoic era.

3 Summary remarks

For a long time, the Qinghai-Tibetan Plateau uplift is considered as the predominant force for climate evolution in East Asia during the late Cenozoic. A synthesis of existing studies in this paper suggests that the uplift may not be the most important driving force for the monsoon and arid climate evolution, because there are many disagreements between the timing and amplitude of the Qinghai-Tibetan uplift and the evolution and variation of the monsoon and dry climate. On the other hand, the synchronous variation and evolution of the monsoon and the dry climate with the global ice volume/high-latitude temperature change during late the Cenozoic suggest that the global cooling might be a major driver for the EAC evolution after it was initially formed at 22–25 Ma. The global ice volume/temperature changes may have triggered a series of interactions between the land and the ocean, and the land surface and the atmosphere. This could cause changes in the monsoon track and moisture source. The changes in the global temperature could affect the EAC through the changes in the atmospheric circulation patterns. In addition, the high-latitude temperature change may lead to the shift of the ITCZ, which controls the location of the monsoon precipitation belt and the dry climate.

However, none of these hypotheses aforementioned by itself can fully explain the climate evolution and variation in East Asia during late Cenozoic. This is because each of these factors influenced the EAC, but the roles they played change with time and space. In addition, these factors also interact with each other, and the interactions also vary in time and space. Future studies should aim to obtain and analyze high-resolution geological record of past climate change and tectonic evolution, and to integrate geological study with numerical modeling. These hold the key to understanding the evolution and variation of Eastern Asian monsoon and the dry climate during late Cenozoic.

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