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Impact of Topography and Land-Sea Distribution on East Asian Paleoenvironmental Patterns

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ABSTRACT

Much geological research has illustrated the transition of paleoenvironmental patterns during the Cenozoic from a planetary-wind-dominant type to a monsoon-dominant type, indicating the initiation of the East Asian monsoon and inland-type aridity. However, there is a dispute about the causes and mechanisms of the transition, especially about the impact of the Himalayan/Tibetan Plateau uplift and the Paratethys Sea retreat. Thirty numerical sensitivity experiments under different land-sea distributions and Himalayan/Tibetan Plateau topography conditions are performed here to simulate the evolution of climate belts with emphasis on changes in the rain band, and these are compared with the changes in the paleoenvironmental patterns during the Cenozoic recovered by geological records. The consistency between simulations and the geological evidence indicates that both the Tibetan Plateau uplift and the Paratethys Sea retreat play important roles in the formation of the monsoon-dominant environmental pattern. Furthermore, the simulations show the monsoon-dominant environmental pattern comes into being when the Himalayan/Tibetan Plateau reaches 1000–2000 m high and the Paratethys Sea retreats to the Turan Plate.

Key words: Paratethys Sea retreat, Himalayan/Tibetan Plateau uplift, paleoenvironmental pattern, precipitation field, Turan Plate

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1. Introduction

Previous geological studies (Zhou, 1982; Wang, 1990; Liu and Guo, 1997; Zhang and Guo, 2005) have illustrated that the Paleogene paleoenvironmental pattern in China was dominated by roughly-zonal climates resulting from the planetary wind system (Fig. 1a). Conspicuous changes had occurred for the Neogene when the originally-arid southwestern and southeastern parts of the country became much more humid and the geographic location of the arid region in the northern part of China was closer to the present-day one (Fig. 1b), indicating the initiation of the East Asian monsoon and inland-type aridity. The Paleogene paleoenvironmental pattern was called the "planetary-wind-dominant type" and the Neogene paleoenvironmental pattern was called the "monsoon-dominant type" by geologists (Guo, 2003; Zhang and Guo, 2005).

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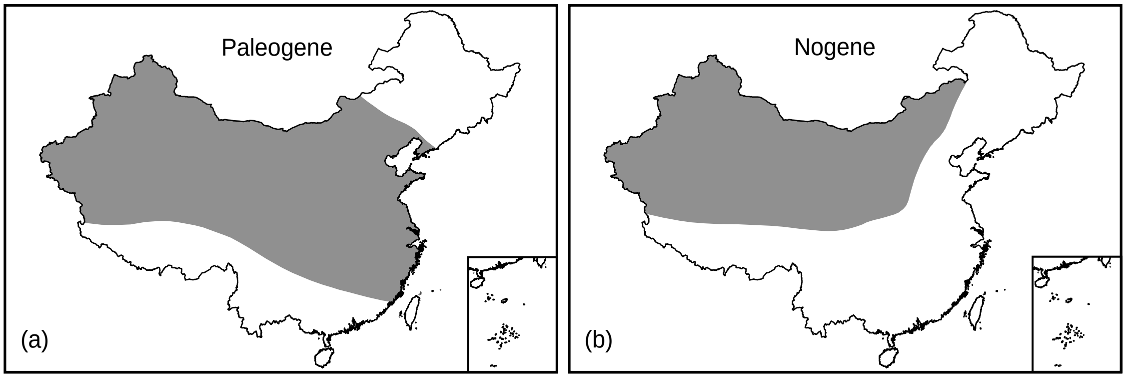

Fig. 1. Change of paleoenvironmental patterns in China during the Cenozoic. (a) Paleogene paleoenvironmental pattern of planetary-wind-dominant type, (b) Neogene paleoenvironmental pattern of planetary-wind-dominant type (modified from Zhang and Guo, 2005). Arid areas are shaded.

However, there is a dispute about the reasons and mechanisms for the transition mentioned above, especially about the impact of the Tibetan Plateau uplift and the Paratethys Sea retreat. Many numerical experiments (Kutzbach et al., 1989; Prell and Kutzbach, 1992; Chen et al., 1999; An et al., 2001; Liu et al., 2001; Liu and Yin, 2002; Wu, 2004) have underlined the impact of the Tibetan Plateau uplift on the Asian monsoon. Kutzbach et al. (1989) found that progressive uplift could cause a monsoon-like circulation to develop in the vicinity of the Tibetan Plateau in July. Prell and Kutzbach (1992) analyzed the output from a series of AGCM (atmospheric general circulation model) sensitivity experiments and concluded that the impact of the plateau uplift was more important than Earth orbital parameters, atmospheric CO_2 concentration, and the glacial-age lower boundary conditions in influencing the South Asian summer monsoon. The East Asian monsoon was also sensitive to the uplift of the plateau (An et al., 2001; Liu and Yin, 2002; Wu, 2004), and the plateau uplift could greatly change the rainband in the East Asian area (Liu et al., 2001). But, other studies have paid more attention to the land-sea distribution conditions (Ramstein et al., 1997; Fluteau et al., 1999; Wu, 2004). Ramstein et al. (1997) emphasized the impact of the evolution of the land-sea distribution conditions induced by the retreat of the Paratethys Sea (an epicontinental sea) and thought that the retreat shifted the central Asian climate from temperate to continental conditions and played a role as important as the uplift of the Himalayan/Tibetan Plateau in driving the Asian monsoon changes.

To the question mentioned above, we attempt to use the IAP AGCM (the AGCM developed at the Institute of Atmospheric Physics/the Chinese Academy of Sciences) model to run 30 sensitivity numerical experiments under different Paratethys Sea and Tibetan Plateau topography conditions, and compare the precipitation field patterns simulated in China with paleoenvironmental patterns reconstructed by geological records (Zhou, 1982; Wang, 1990; Liu and Guo, 1997; Zhang and Guo, 2005) in order to figure out the causes of the paleoenvironmental pattern transitions during the Cenozoic.

2. Model and experimental design

2.1 *Model*

The IAP AGCM used in this paper is a global grid point model with 5° (lon)×4° (lat) horizontal resolution and nine unequal levels in the vertical, with the upper model boundary at 10 hPa. The model uses the gravity wave-drag scheme to deal with the impact of topography on atmospheric circulations and fully considers the interaction between atmosphere and ocean, soil, and vegetation. The simulation of the modern climate by the IAP AGCM is consistent with the observed, indicating that the model has unique characteristics in its model dynamics and computational scheme and has its own features in the model physics (Bi, 1993). Other detailed descriptions of the model can be found in Liang (1996) and Bi (1993). Furthermore, the model has powerful abilities to simulate paleoclimate and has successfully simulated the Mid-Holocene (Wang, 1999; Wei and Wang, 2004) and the Last Glacial Maximum (Jiang et al., 2003) climate in China.

2.2 *Boundary conditions and experiment designs*

Geological evidence illustrates the process of the Paratethys Sea retreat. The sea once divided the Eurasian continent into two parts (Jin et al., 1995), then separated from the Arctic Ocean (Akhmet'ev et

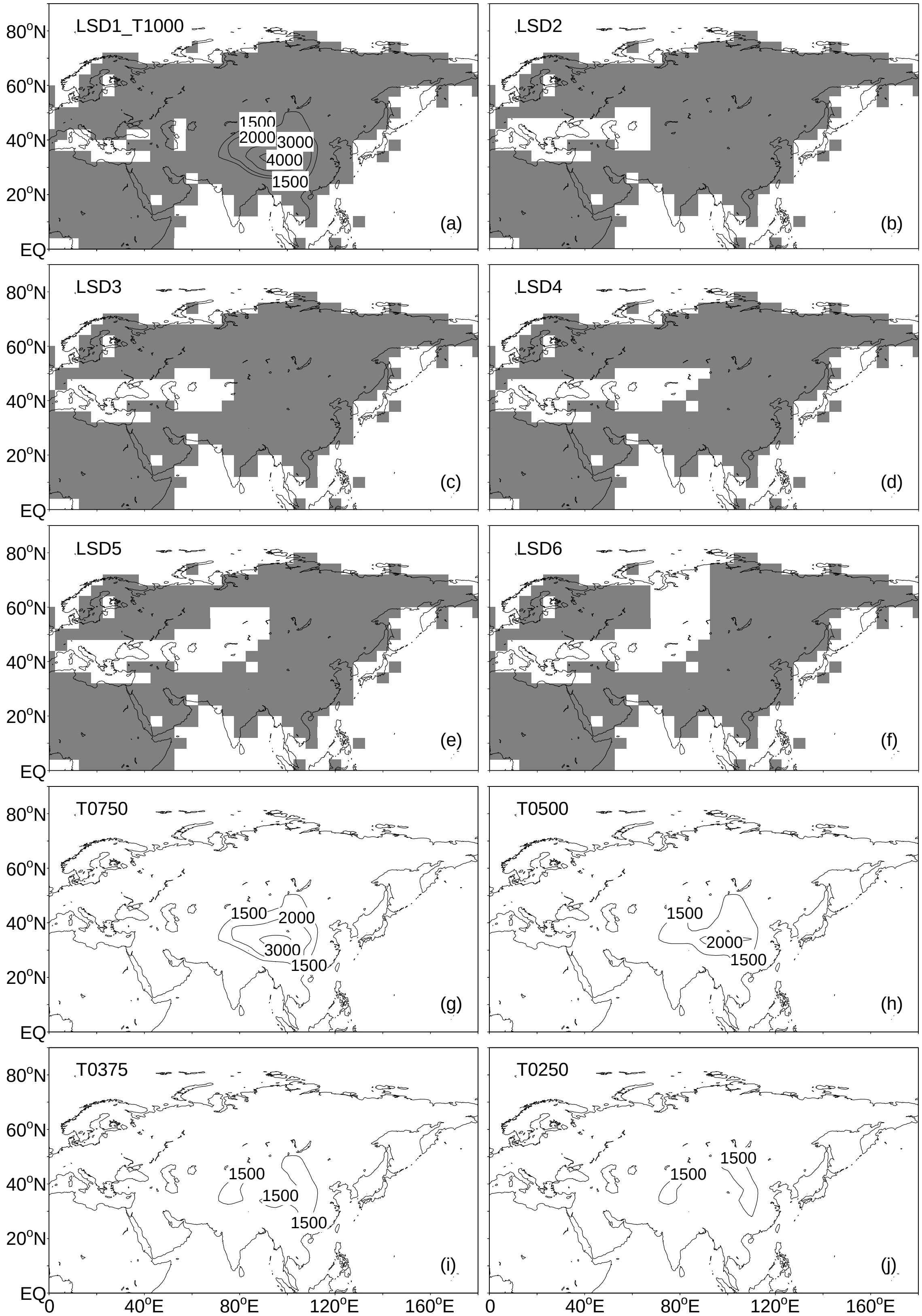

Fig. 2. Paratethys Sea and Himalayan/Tibetan Plateau conditions. (a)–(f) the Paratethys Sea conditions, where land areas are shaded; (a) and (g)–(j) the Himalayan/Tibetan Plateau conditions.

Table 1. Topographic conditions of the Himalayan/Tibetan Plateau.

Conditions	Max (m)	Mean (m)	Areas higher than 1500 m*	
			Tibet	East Asia
T1000	4472	About 3000	20	36
T0750	3354	About 2100	20	36
T0500	2236	About 1600	15	28
T0375	1793	About 1300	9	21
T0250	1528	About 1000	1	13

*The column is used to illustrate how many points are higher than 1500 m in the Tibetan and East Asian areas in the topographic conditions

al., 2001) and became closed step by step (Ramstein et al., 1997). According to the above process, six land-sea distribution (LSD) conditions are designed here to represent different stages of the retreat (Fig. 2a–f). The Paratethys Sea connects to the Arctic Ocean in the LSD6 condition. The LSD5 condition is similar to the land-sea distribution condition of 30 Ma B. P. designed by Ramstein et al. (1997). The sea retreats to the southern part of Siberia in the LSD4 condition, and to the Turan Plate in the LSD3 condition. The LSD2 condition is close to that of 10 Ma B. P. designed by Ramstein et al. (1997). And the LSD1 condition is the land-sea distribution of today.

The Himalayan/Tibetan Plateau was gradually uplifted during the collision of the Indian plate and the Eurasian plate (Harrison et al., 1992; Tapponnier et al., 2001). Five topographic conditions are designed here to represent the plateau uplift (Figs. 2a, g–j). We describe at every grid point in the area (30°–42°N, 75°–100°E)to be 100%, 75%, 50%, 37.5%, and 25% of the elevation originally prescribed by the IAP AGCM to obtain the five topographic conditions, called T1000, T0750, T0500, T0375, and T0250, respectively (Table 1). The height of the plateau designed in the paper ranges from 1000 m to 3000 m.

Except for the plateau topography and the Paratethys Sea conditions, all other boundary conditions in the experiments remain unchanged because previous studies (e.g., Kutzbach et al., 1998; Wang, 1999; Jiang et al., 2003) have illustrated that SSTs, Earth orbital parameters, atmospheric CO_2 concentration, vegetation and the glacial-age lower boundary conditions can impact the intensity of monsoon circulations and precipitations but cannot change the basic precipitation field patterns with deficient rain areas in the central regions of the country. Furthermore, the other purpose of such a simplified design is to isolate the impact of the plateau uplift and Paratethys Sea retreat from those of other forcing mechanisms.

SSTs and ice-sheet data of the Middle Pliocene recovered by Dowsett et al. (1999) are used in all experiments, for the study mainly involves the geological course of the Miocene and Pliocene, which have been generally warmer in the Cenozoic with continental ice-sheets only in the south polar areas (Zachos et al., 2001). The SSTs are available for Feburary and August only, so a sinusoidal variation with extremes in February and August is used to get monthly-varying SSTs. Additional sea points due to the Paratethys Sea opening are given the same SSTs as the neighboring sea point(s) at the same latitude. Earth orbital parameters and vegetation use the conditions of today. The atmospheric CO_2 concentration is set to 345 ppmv in all experiments.

Under the above boundary conditions, we compose five Plateau topography and six Paratethys Sea conditions and thus design 30 experiments to simulate the East Asian climate with emphasis on the precipitation fields. All experiments run for 12 years, and the results reported here are ensemble averages of the last 10 years.

3. Simulation results and analysis

The simulation results illustrate that there are two kinds of precipitation field patterns in China (Fig. 3). In the first kind, the rain band with rainfall less than 1.5 mm d^{-1} is zonally distributed in the northern part of China. However, in the other kind, the rain band with rainfall less than 1.5 mm d^{-1} is distributed in the western part of China and the original zonal deficient rain areas disappear. The first kind of precipitation field is simply called type I, and the second kind type II.

All results in the 30 experiments are summarized in Table 2. The table shows that, when the Himalayan/Tibetan Plateau is about 3000 m high in the T1000 topography condition, the precipitation fields of type II are simulated under the LSD5 to LSD1 Paratethys Sea conditions, and the fields of type I are simulated under the LSD6 condition. However, when the plateau is about 1000–2000 m high in the other

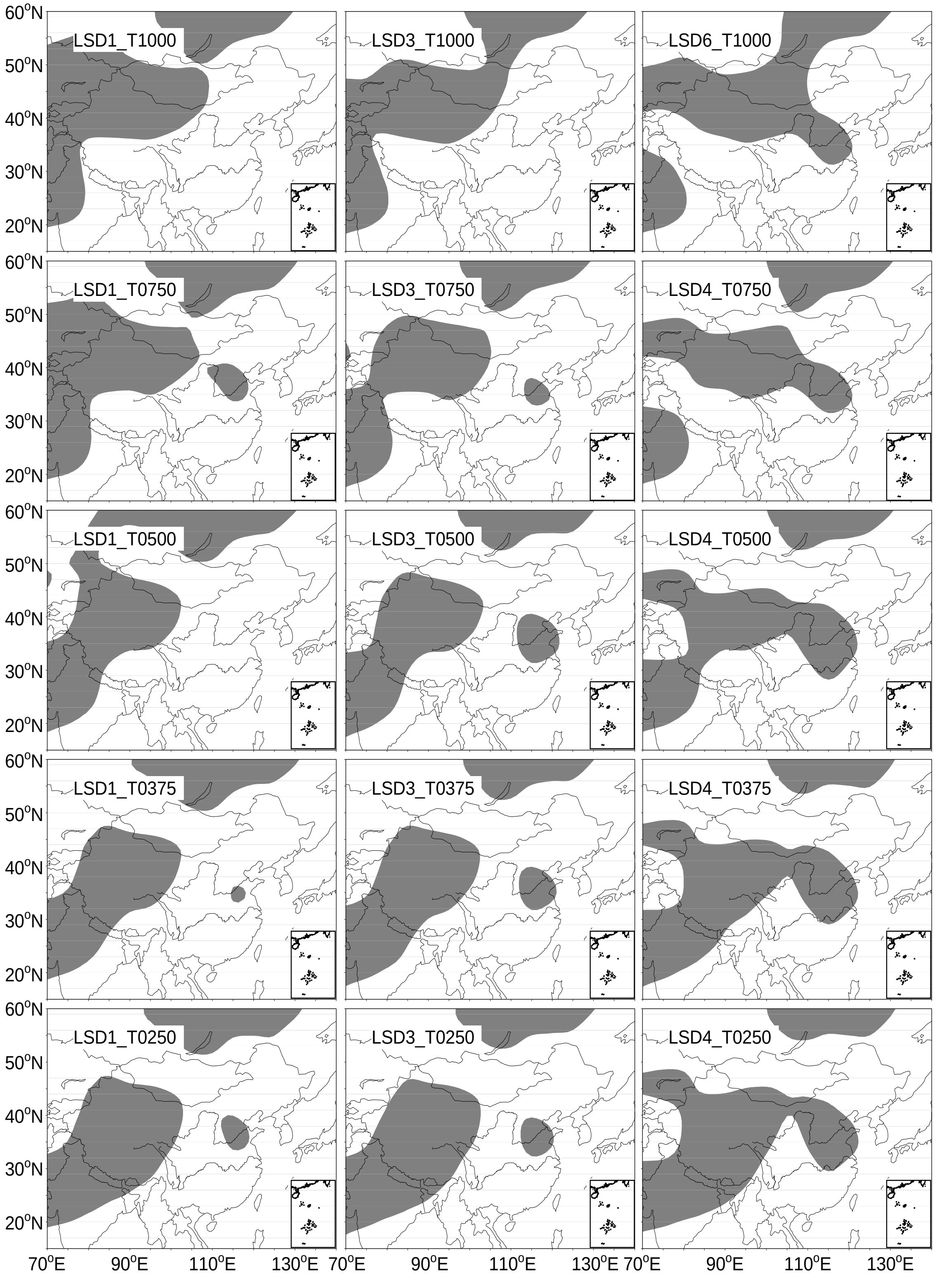

Fig. 3. Precipitation field patterns in China simulated in the numerical experiments (partial results). The figure only distinguishes between the areas with rainfall less than 1.5 mm d^{-1} and the areas with rainfall more than 1.5 mm d^{-1} in order to clearly show the difference in precipitation field patterns in China. The areas with rainfall less than 1.5 mm d^{-1} are shaded.

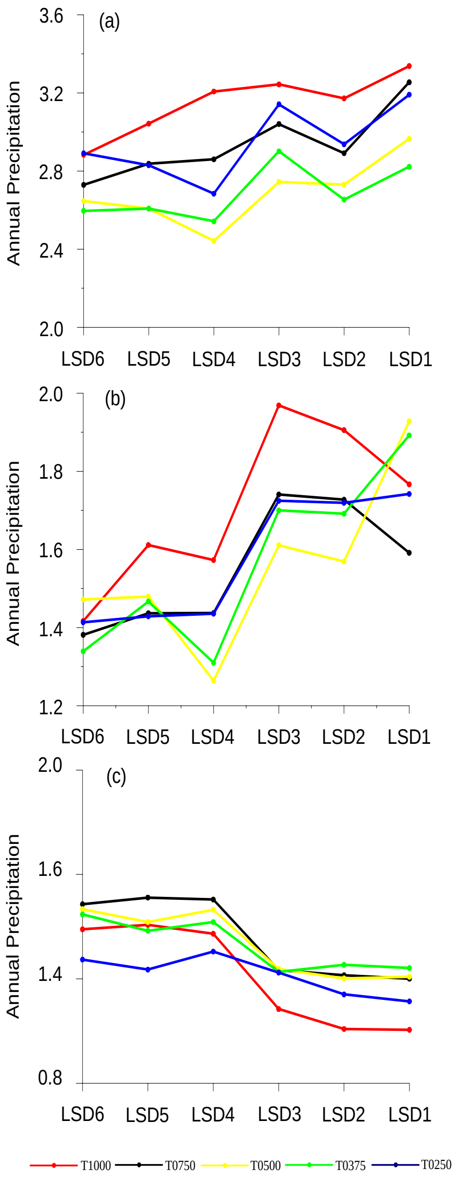

Fig. 4. Regional average values of annual rainfall simulated in all 30 experiments in three parts of China (mm d^{-1}). (a) SM (22°–30°N, 105°–120°E) areas, (b) NM (34°–42°N, 105°–120°E) areas, (c) WC (34°–46°N, 75°–95°E) areas.

Table 2. Precipitation field patterns simulated in all 30 experiments.

	Paratethys					
Plateau	LSD1	LSD2	LSD3	LSD4	LSD5	LSD6
T1000	II	II	II	II	II	I
T0750	II	II	II	I	I	I
T0500	II	II	II	I	I	I
T0375	II	II	II	I	I	I
T0250	II	II	II	I	I	I

four (from T0750 to T0250) topography conditions, the precipitation fields of type II are simulated under the LSD1 to LSD3 Paratethys Sea conditions and the fields of type I are simulated under the other conditions. The transition of the precipitation field patterns takes place between the LSD3 and LSD4 conditions.

Following a previous study (Liu and Yin, 2002), the regional average values of annual rainfall in three parts of China are calculated for three regions: the Yangtze River valley in China and the area south of it (22°–30°N, 105°–120°E, denoted SM), the Yellow River valley and the area north of it (34°–42°N, 105°–120°E, denoted NM), and the western part of China (34°–46°N, 75°–95°E, denoted WC). The results illustrate the increasing trend of rainfall in SM and NM and the decreasing trend in WC. Furthermore, the rainfall remarkably increases in SM and NM and decreases in WC between the LSD4 and LSD3 Paratethys Sea conditions. These shifts can be attributed to the intensification of the East Asian monsoon circulations (Fig. 5) during the transition of precipitation field patterns.

Table 2 also illustrates that precipitation fields of type II are simulated under the LSD3, LSD2 and LSD1 Paratethys Sea conditions and under all five Plateau conditions. These 15 results indicate that the further uplift of the Tibetan Plateau and further retreat of the Paratethys Sea cannot change the pattern of precipitation fields as soon as the fields of type II form. However, the further retreat can increase rainfall in SM and slightly decrease rainfall in WC, but the trend of rainfall in NM is not clear (Fig. 4). Furthermore, the further plateau uplift can also increase rainfall in SM and decrease rainfall in WC. In NM, the rainfall has clear fluctuations, but the variation tendency is slightly reduced (Fig. 6). The regional average values of the Mw monsoon index defined by Liu and Yin (2002) and the angle of summer wind and winter wind (Fig. 6) are calculated to illustrate the impact of the Tibetan Plateau on the monsoon circulations; the higher the values, the more intense the monsoon circulations. Figure 6 shows the increasing trend of the Mw index and the angle in the SM and the NM areas, indicting the intensification of monsoon circulations during the plateau uplift. The result is consistent with a previous study (Liu and Yin, 2002). If we use the criterion that the angle of summer wind and winter wind should be greater than 120° to define the monsoon, then the Tibetan Plateau that is about 2000 m high in the T0750 and T1000 topography conditions can induce strong monsoon circulations in SM under the land-sea distribution conditions of today, and the plateau that is about 3000 m high can induce strong monsoon circulations in NM. The results also support the early study by Kutzbach et al. (1989).

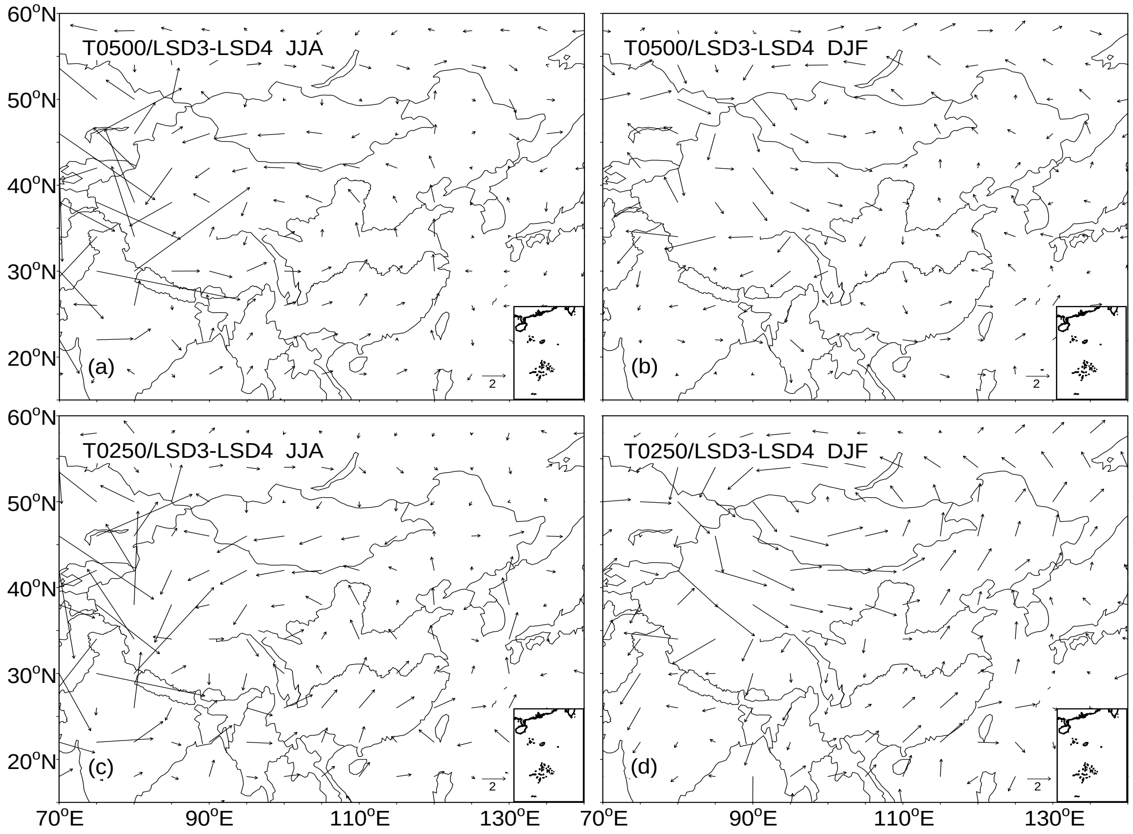

Fig. 5. 850-hPa wind differences between the LSD4 and LSD3 conditions (m s^{-1}). (a) wind differences for summer under T0500 topographic conditons, (b) wind differences for winter under T0500 topographic conditons, (c) wind differences for summer under T0250 topographic conditions, (d) wind differences for winter under T0250 topographic conditons.

Our results that highly consist with the early studies (Kutzbach et al., 1989; Liu et al., 2001; Liu and Yin, 2002; Ramstein et al., 1997) confirm the important impact of the plateau uplift and the Paratethys Sea retreat on the intensification of the East Asian monsoon. These two factors can strengthen monsoon circulations, increase rainfall in the monsoon areas and decrease rainfall in the western part of China. Furthermore, our results indicate that precipitation fields of type II form when the Paratethys Sea retreats to the Turan Plate and the Tibetan Plateau is about 1000–2000 m high.

A previous study (Liu et al., 2001) also illustrated a similar transition of precipitation field patterns during the plateau uplift. The precipitation fields similar to those of type I in the paper were simulated under the land-sea distribution conditions of today, when the height of the plateau was lower than 1000 m. The precipitation fields similar to those of type II were simulated when the height of the plateau was higher than 1000 m. The further uplift could not change the pattern of the precipitation fields.

In summary, our results based on a different AGCM indicate that both the Paratethys Sea retreat and Tibetan Plateau uplift are key factors in the transition of the East Asian precipitation field patterns, and the results support the previous conclusion (Ramstein et al., 1997) that the Paratethys Sea retreat plays a role as important as the uplift of the Himalayan/Tibetan Plateau in driving the Asian monsoon.

4. Comparisons between simulations and geological evidence

Generally, the areas with rainfall ranging from 200 mm d^{-1} to 400 mm d^{-1} are semi-arid regions, and the areas with rainfall less than 200 mm d^{-1} are arid regions (Wu et al., 2000). In the simulations of modern climate by the IAP AGCM, the position of the 1.5 mm d^{-1} isohyet is close to that of the observed 400 mm d^{-1} isohyet, and 1.5 mm d^{-1} is approximately 547 mm d^{-1}, which is close to 400 mm d^{-1}; therefore, the areas with rainfall less than 1.5 mm d^{-1} in the simulations can

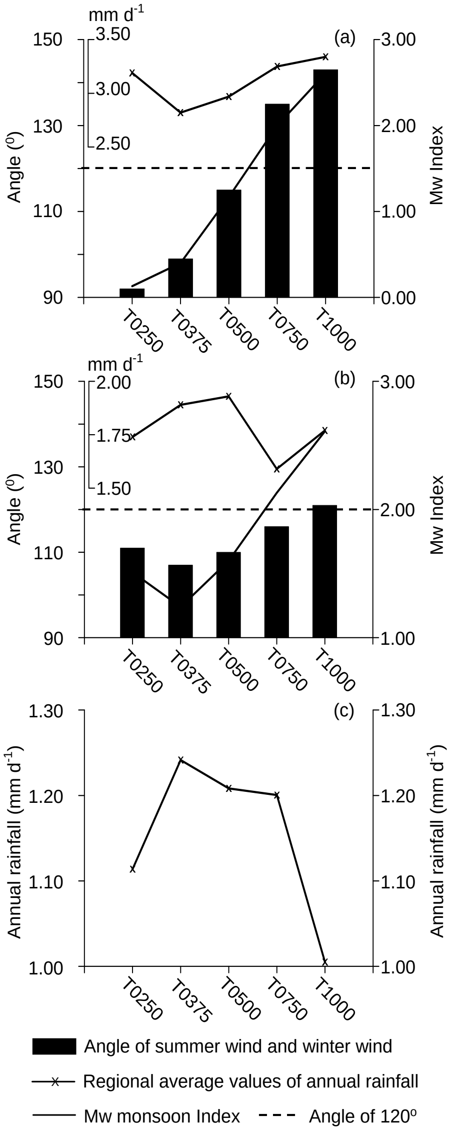

Fig. 6. Regional average values of annual rainfall, Mw monsoon index and angle of summer wind and winter wind in five experiments simulated under different plateau topography and LSD1 conditions. (a) SM (22°–30°N, 105°–120°E) areas, (b) NM (34°–42°N, 105°–120°E) areas, (c) WC (34°–46°N, 75°–95°E) areas.

be regarded as semi-arid/arid regions, which can be compared with the geological evidence (Zhou, 1982; Wang, 1990; Liu and Guo, 1997). Hence, the precipitation fields of type I simulated with the roughly-zonal rain band are highly similar to the Paleogene paleoenvironmental pattern (Fig. 1a), and the precipitation fields of type II can be compared to the Neogene paleoenvironmental pattern (Fig. 1b).

Our results and the previous study by Liu et al. (2001) illustrate that the transition of the precipitation field patterns is consistent with the above change in paleoenvironmental patterns (Zhou, 1982; Wang, 1990; Liu and Guo, 1997; Zhang and Guo, 2005) during the Plateau uplift and the Patatethys Sea retreat. The consistency indicates that both the retreat and the uplift are key factors that can induce the above transition of paleoenvironmental patterns during the Cenozoic. These above two factors strengthen monsoon circulations, increase rainfall in the monsoon areas and decrease rainfall in the western part of China. They play the same roles in the above paleoenvironmental patterns' transition. Furthermore, our results have determined that the Himalayan/Tibetan Plateau being about 1000–2000 m high and the Paratethys Sea retreating to the Turan Plate are the important boundary conditions for the transition.

Our study shows that when the precipitation fields of type II form, further retreat and uplift cannot change the precipitation field patterns in China, but they can reduce rainfall and increase aridity in the western part of China. A geological study (Liu and Guo, 1997) also illustrates that the environmental patterns are a monsoon-dominant type in both the Miocene and Pliocene and hence supports our results. And the Tibetan uplift in the Pliocene (Li and Fang, 1999) shows the high consistency with the intensification of aridity in the interior land areas of Asia in 3.6 Ma. B. P. (Guo et al., 2004).

5. Summary

This paper considers the Tibetan Plateau uplift and the Paratethys Sea retreat at the same time, and performs 30 sensitivity numerical experiments to explore the causes of paleoenvironmental patterns' transitions during the Cenozoic. Our results clearly show that the Paratethys Sea retreat and the Tibetan Plateau uplift can remarkably change the climate in China. When the Tibetan Plateau is about 1000–2000 m high and the Paratethys Sea retreats to the Turan Plate, the precipitation fields of type II will form, and further uplift and retreat can reduce rainfall and increase aridity in the western part of China but cannot change the pattern of the precipitation fields. The precipitation fields of types I and II are similar to the Paleogene and the Neogene paleoenvironmental patterns, respectively. The transition of the simulated precipitation field patterns is consistent with that of the paleoenvironmental patterns during the Cenozoic. The consistency indicates that both the Paratethys Sea retreat and the Tibetan Plateau uplift are key factors that induce the transition of the paleoenvironmental pattern from "plantery-wave-dominant type" to "monsoon-dominant type".

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