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The Tibetan Plateau as amplifier of orbital-scale variability of the East Asian monsoon

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[1] Asian monsoon climate variability at geological time scales is modulated by both the Earth's orbital changes and tectonic uplift of the Tibetan Plateau (TP). Here, using bandpass-filtered versions of previously-published high-resolution geological records from Chinese loess, we show that the orbital-scale variability of the East Asian summer monsoon (EASM) has increased dramatically since the late Pliocene. Climate model simulations indicate that the increase in the variability of the northern EASM at both precession and tilt periods may be, at least partially, attributed to the uplift of the TP. *INDEX TERMS:* 1620 Global Change: Climate dynamics (3309); 3322 Meteorology and Atmospheric Dynamics: Land/atmosphere interactions; 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; 3374 Meteorology and Atmospheric Dynamics: Tropical meteorology; *KEYWORDS:* Tibetan Plateau, Orbital forcing, East Asian monsoon. **Citation:** Liu, X., J. E. Kutzbach, Z. Liu, Z. An, and L. Li, The Tibetan Plateau as amplifier of orbital-scale variability of the East Asian monsoon, *Geophys. Res. Lett.*, *30*(16), 1839, doi:10.1029/2003GL017510, 2003.

[2] The Asian monsoon has two major components, the South Asian (Indian) monsoon and the East Asian (Chinese) monsoon [*Lau and Li*, 1984]. The loess-paleosol sequence together with the underlying Red Clay sequence on China's Loess Plateau northeast of the TP constitutes a continuous record of climate change of the East Asian monsoon over the past 7–8 million years (Ma) [*An et al.*, 2001]. Spectral analyses of proxy time series from the Loess Plateau show strong orbital periodicities, including the 100-kyr, 41-kyr and 21-kyr cycles [*Kukla et al.*, 1990; *Ding et al.*, 1994]. Magnetic susceptibility of loess and Red Clay on the Chinese Loess Plateau have been used as proxy indices of the EASM [*An et al.*, 1991, 2001] and additional techniques are being developed [*Guo et al.*, 2000]. Figure 1 shows linearly-detrended and bandpass-filtered precession (14–28 kyr) and obliquity (33–49 Kyr) components of the EASM manifested by magnetic susceptibility of loess at Hejiayao (HJY) and Zhaojiachuan (ZJC) during the past 6 Ma; estimates of precession and obliquity [*Berger and Loutre*, 1991] are also shown. The original magnetic susceptibility data at HJY and BJZ were taken from *An et al.* [1998], [2001], respectively; see these texts for details of sampling, measuring and dating. The variability (amplitude) of the EASM at these orbital periods has increased markedly since about 2.8 Ma at both sites. In contrast, the variability of the orbital parameters is stable over the last 6 Ma. Assuming that the 21-kyr-centric and 41-kyr-centric periodic components of the EASM are a linear response to the orbital forcing with appropriate lags [*Imbrie et al.*, 1992], then other mechanisms must cause the augmentation in the variability of the EASM since 2.8 Ma (Figure 1). One such mechanism may be the uplift of the TP, as suggested in modeling studies of the South Asia monsoon [*Prell and Kutzbach*, 1997].

[3] To explore the possible role of uplift in modulating the response of the EASM to orbital forcing, we completed eight numerical experiments (Table 1) with the version 2.01 of the National Center for Atmospheric Research-Community Climate System Model (NCAR-CCSM) [*Blackmon et al.*, 2001], in which the atmospheric model, with spectral triangular truncation at wave number 31 in the horizontal (~3.75° of latitude and longitude) and with 26 levels in the vertical, is fully coupled to a land model; the oceanic boundary uses seasonally varying prescribed climatological sea surface temperatures (SSTs) and sea ice. The horizontal and vertical resolution of the model used here is considerably higher than was used in previous studies [*Prell and Kutzbach*, 1997]. Under conditions of present-day mountains (M) and no mountains (N), we examine the response of the EASM to: (i) the change in precession (longitude of perihelion) from the present-day situation with perihelion in northern winter (PW) to the opposite situation with perihelion in northern summer (PS); and (ii) the change in obliquity (tilt of Earth's axis) from a low angle of 22.2° (TL) to a high angle of 24.4° (TH) (the present-day value is 23.44°). Each experiment was integrated for 10 years and the mean for the last 5 years is used in our analyses.

[4] We first compare low-level winds averaged for summer (June–August) in M and N simulations for present-day orbital forcing (Figures 2a and 2b). In the simulation with the TP (M), the circulation consists of cyclonic flow around the TP, with westerly flow over India and southerly flow over eastern China. Without the TP (N), however, the southerly flow over eastern China is reduced markedly while the westerly flow over India is reduced only slightly. This difference between the two simulations implies that the TP may play a very important role in controlling the strength of the EASM as discussed previously [*Liu and Yin*, 2002].

[5] With present-day orography (M), the enhancement of northern summer insolation induced by precession changes (MPS-MPW) causes an intensification of the cyclonic circulation around the TP (Figure 2c); the southerly wind over northern East Asia, as well as the southwesterly wind north of the Bay of Bengal and the northeasterly wind east

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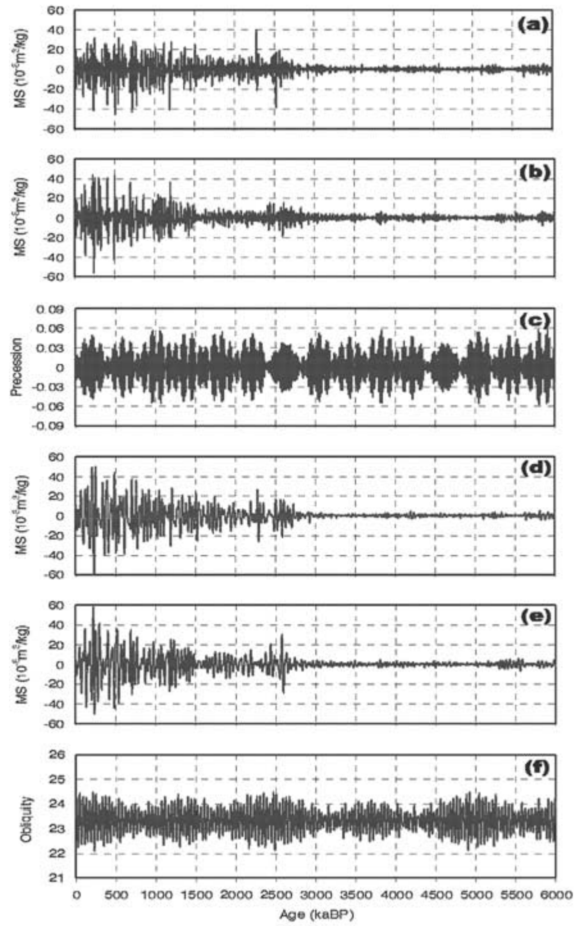

Figure 1. Linearly-detrended precessional and obliquity periodic components of the East Asian summer (JJA) monsoon reflected by magnetic susceptibility (MS) of loess at two sites on the Chinese Loess Plateau and the corresponding orbital parameters during the past 6 million years. (a) 14–28 kyr bandpass-filtered MS at Hejiayao (HJY, 35°20′N, 107°E); (b) 14–28 kyr band-pass filtered MS at Zhaojiachuan (ZJC, 35°53′N, 107°58′E); (c) parameter of climatic precession (eccentricity times sine of longitude of perihelion); (d) 33–49 kyr bandpass-filtered MS at HJY; (e) 33–49 kyr band-pass filtered MS at ZJC; (f) parameter of obliquity (degrees of tilt of Earth's axis) (the data of the two orbital parameters from *Berger and Loutre* [1991]). Standard low-pass and high-pass filters were used to construct the band-pass filtered time series.

of the Caspian Sea, are enhanced. Associated with the strengthened winds, the upward vertical motion is also reinforced in these three regions, as is precipitation and additional heating of the air by the associated condensation of water vapor (not shown). Therefore, the intensified monsoon circulation (MPS-MPW) is driven initially by the insolation increase associated with the enhanced precessional forcing and subsequently by the additional release of heat by condensation. This positive feedback between the low-level circulation and the diabatic heating maintains an intensified Asian summer monsoon, compared to present.

[6] In the absence of mountains, the cyclonic circulation and vertical motion (and precipitation) is also intensified in

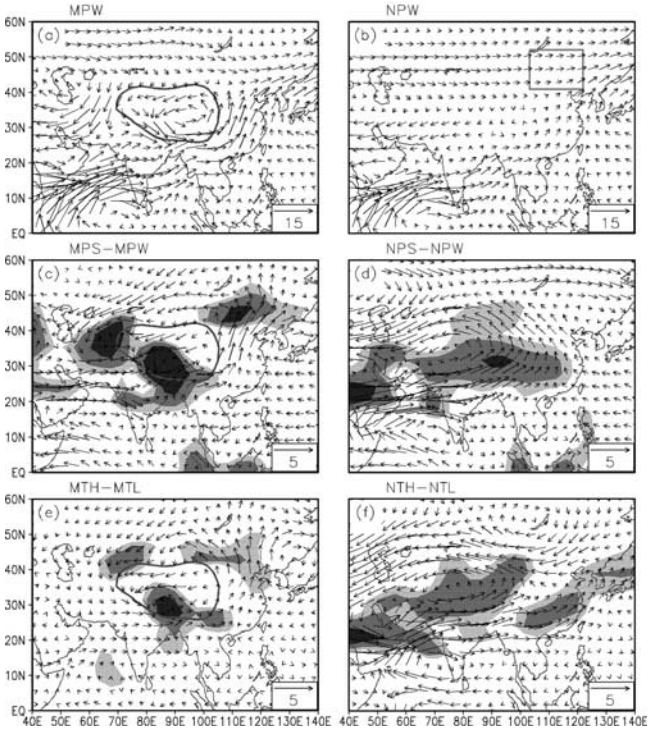

Figure 2. Simulated summer-averaged (JJA) horizontal winds (m/s, see vector length keys) in the lower troposphere (~867 hPa, i.e., the 4th σ level of the model's atmosphere) and mass-weighted averaged vertical velocity from the surface to 300 hPa for experiments with mountains (M) (left) and without mountains (N) (right). (a) MPW (modern control run). The solid line indicates the 2000m contour of the Tibetan Plateau (same in (c) and (e)); (b) NPW (modern insolation but no mountains). The box defines the northern East Asia (NEA) region used for statistics in Figure 3; (c) MPS-MPW; (d) NPS-NPW; (e) MTH-MTL; (f) NTH-NTL. Here (c) and (d), and (e) and (f) show, respectively, differences between two experiments with strong and weak insolation forcing over Asia in JJA. See text. Only areas with prominently enhanced upward motion are shaded (light −5 ~ −10*1000 kPa/s; medium −10 ~ −20*1000 kPa/s; heavy < −20*1000 kPa/s).

Table 1. Experiments and Their Orographic and Orbital Conditions.

Name of Exp.	Orography	Precession	Obliquity
MPW	Yes	102.72	23.44
MPS	Yes	282.72	23.44
NPW	No	102.72	23.44
NPS	No	282.72	23.44
MTL	Yes	102.72	22.20
MTH	Yes	102.72	24.40
NTL	No	102.72	22.20
NTH	No	102.72	24.40

Each experiment has a name composed of 3 capital characters, in which the first character "M" or "N" indicates modern mountains (M) or no mountains (N, setting the elevations to 200m where the present-day elevations are above 200m in the Eurasian continent from 20° to 140°E). The characters "PW" or "PS" means the case with precession-induced weak or strong insolation in boreal summer, while "TL" or "TH", mean that tilt is low (TL) or high (TH). "Precession" and "Obliquity" indicate the longitude of perihelion (degree) and the tilt of Earth's axis (degree), respectively. MPW is the present-day control experiment.

response to the precession-induced increase of insolation (NPS-NPW, Figure 2d), however the intensification is largely concentrated in a zonal belt 25°–35°N over the Asian continent. The intensified low-level cyclone over western Asia is initiated by the insolation change, being independent of any orography effects, and resembles the response found in linear model integrations with prescribed atmospheric heating [*Rodwell and Hoskins*, 1996]. There is strong enhancement of the circulation response by the moisture advection and condensational heating over South Asia. The topography substantially modifies the response of the EASM to precessional forcing (Figure 2): there is more intense poleward flow, stronger ascending current, and more rainfall (see below) over northern East Asia in the mountain case, compared with the no-mountain case under the same precessional forcing.

[7] When insolation is increased by changing the tilt of Earth's axis from 22.2° to 24.4°, the general response of the Asian monsoon (MTH-MTL, Figure 2e) resembles that induced by precession (Figure 2c), although the magnitude is smaller. Similarly, in the absence of mountains, the response of the Asian monsoon to tilt forcing (NTH-NTL, Figure 2f) resembles the response to precessional forcing (Figure 2d).

[8] We summarize, in Figure 3, the simulated changes of precipitation and circulation intensity for northern East Asia (NEA, area outlined in Figure 2b). The precessionally-driven increase of precipitation in NEA is 6.7% in the case with no mountains, and 30.6% in the case with the TP (Figure 3a). The rainfall decreases with increasing tilt in the no-mountain case, even although the insolation is increased, but increases by 8.6% in response to the same change in tilt when the TP is present. Using a regional monsoon circulation index [*Wang and Fan*, 1999], there is a high consistency between the simulated variations in the regional precipitation and the circulation intensity (Figure 3b). The intensification in the monsoon circulation over East Asia is augmented by dynamical effects of meridional vorticity advection and northward migration of the upper jet stream as described elsewhere [*Liang and Wang*, 1998] as compared with the more direct dynamical response to condensational heating over South Asia.

[9] The response of the northern EASM to the two different orbital forcings, precession and obliquity, is similar. Given that the most fundamental aspect of monsoon forcing is land-sea temperature contrast [*Webster*, 1987] and that SSTs are prescribed with climatological values, the initiation of changes of the Asian monsoon in our simulations depends on the change of land temperature. Both kinds of orbital forcing (PS-PW and TH-TL) induce increased area-average insolation over land: about 22 W/m^2 and 9.5 W/m^2, respectively (Table 2). In response, there are changes in total atmospheric heating in the region corresponding to the southern flank of the Tibetan Plateau that are 3–6 times as large as the insolation changes (Table 2). The response of land temperature to precession change is 0.1–0.2°C larger than the response to obliquity change, consistent with the different magnitudes of the area-average forcing; however, the temperature response is partially reduced because of increased precipitation and cloud cover. Although the precession and tilt forcings have opposite latitudinal gradients (Table 2), we conclude, given

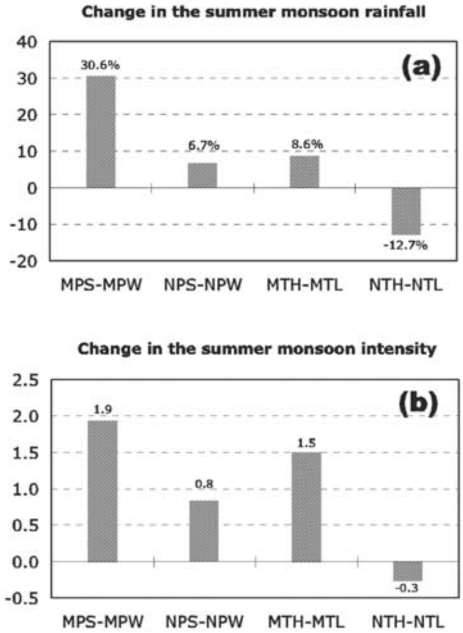

Figure 3. Simulated changes in the summer monsoon rainfall (a) and intensity (b) over the northern East Asian (NEA, 40.82°–51.95°N, 103.13°–121.88°E) region (shown in Figure 2b). The change of rainfall is represented in regionally-averaged percentage. The monsoon intensity is measured with the mean low-level meridional wind at the south boundary for NEA. For the purpose of plotting, differences of monsoon indexes are normalized for each region.

the similarity in pattern of the responses to both kinds of forcing, that the changes in area-averaged insolation, total atmospheric heating, and land-sea thermal contrast appear to be more important than changes in insolation gradient (at least in these experiments with prescribed SSTs).

[10] As described earlier, we also found that the response of the EASM circulation and precipitation to orbital forcing was amplified in the presence of the TP, compared to the simulation without the plateau (Figures 2 and 3). This enhanced response is linked to the greatly increased total atmospheric heating in the region corresponding to the southern flank of the Tibetan Plateau in the simulations with mountains (Table 2). It appears that this additional heating, in the presence of mountains, helps force the enhanced southerly flow to the north and east of the plateau in the vicinity of the enhanced EASM (Figure 2), a pattern somewhat similar to that found in earlier studies [*Rodwell and Hoskins*, 1996; *Liang and Wang*, 1998; *Xu and Chan*, 2002].

[11] In summary, high-resolution records from Chinese loess indicate that the amplitudes of precessional and obliquity components of the EASM have increased markedly since about 2.8 Ma. By using an extreme orographic difference (M vs. N), our modeling results show that the response of the northern EASM to both kinds of orbital forcing is enhanced by uplift of the TP. However, we lack sufficient information to describe the elevation of the whole TP as a function of time. Some investigators [*Harrison et*

Table 2. The Simulated Changes of the Summer (JJA) Insolation (W/m^2) at 20, 35, and 50°N and Area-Average Insolation, Total Atmospheric Heating (TAH, W/m^2) and Surface Air Temperature (°C) for the Mid-Latitude Asian Continent Due to Variations of the Orbital Parameters (PS-PW and TH-TL) for Cases With (M) and Without (N) the Orography.

Experiments	MPS-MPW	NPS-NPW	MTH-MTL	NTH-NTL
Insolation at 50.1°N	17.8	17.8	16.7	16.7
Insolation at 35.3°N	22.1	22.1	9.5	9.5
Insolation at 20.4°N	24.8	24.8	3.2	3.2
Area-average Insolation	22.0	22.0	9.5	9.5
Area-average TAH	126.9	71.3	60.7	48.3
Area-average Temperature	1.2	0.6	1.0	0.5

The values represent differences between two experiments (see text). The area-average used for insolation and surface temperature is: 20°–50°N, 40°–140°E, land only; the area-average used for total atmospheric heating is: 25°–30°N, 80°–95°E.

al., 1992; *Molnar et al.*, 1993; *Garzione et al.*, 2000; *Guo et al.*, 2002; *Spicer et al.*, 2003] report that significant increases in altitude of portions of the TP occurred about 8 Ma, or earlier. However, there is other evidence [*Li et al.*, 1997; *Zheng et al.*, 2000, *An et al.*, 2001] that the TP, especially its northern portion, was uplifting rapidly and extending northward and eastward at 3.6–2.6 Ma. In this study, we used the no-mountain experiments to form a maximum contrast with the present-day case and to identify the maximum role of orography in modulating the orbital-scale variability; determining how the climatic response might depend on the spatial details of the uplift sequence have not been addressed (see, however, *An et al.*, 2001, who address this topic in considering the general increase in intensity of both summer and winter monsoons in east Asia in the past several million years). Although observational studies of the EASM [*Kukla et al.*, 1990] had revealed the existence of climatic signals for both precessional and obliquity periods, no previous modeling work had explored separately the role of precessional and obliquity forcing on East Asian monsoon climates. We find that variations of precession and obliquity can both cause changes in the Asian summer monsoon. Moreover, the variability of the northern EASM is amplified markedly by the uplift of the TP. Owing to the limitation of prescribed-SST experiments, the present conclusions need to be examined further with ocean-atmosphere model simulations, beginning perhaps with mixed-layer oceans. While we have demonstrated the role of the TP in amplifying the orbital-scale variability of the EASM, we do not exclude possible effects of other factors, such as ocean dynamics and ocean gateways [*Khodri et al.*, 2001; *An et al.*, 2001], vegetation [*Claussen*, 1997], atmospheric CO_2 concentration, and characteristic glacial cycles [*Clark et al.*, 1999] in further modifying the response to orbital forcing.

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