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Effect of precession on the Asian summer monsoon evolution: A systematic review

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Geological climatic records and model simulations on the Asian summer monsoon climate change induced by insolation forcing of the Earth's precession are systematically reviewed in this paper. The presentation of the questions on the mechanism of the Asian monsoon evolution at the precession band, currently existing debates and future research directions are discussed. Since the early 1980s, more and more observed evidence and simulated results, especially the absolute-dated stalagmite records and orbital-scale transient model runs in the last few years, have indicated that the quasi-20ka period in the Quaternary monsoon climate change is caused by precession. However, debates still exist on the dynamic mechanism how precession affects the Asian monsoon. The "zero phase" hypothesis says that the Asian monsoon is merely controlled by summer insolation in the Northern Hemisphere (NH) while the "latent heat" hypothesis emphasizes the dominant effect of latent heat transport from the Southern Hemisphere (SH) besides the role of the northern insolation. The two hypotheses have separately been supported by some evidence. Although we are cognizant of the importance of northern solar radiation and the remote effect of southern insolation, it has still a long way to go before comprehensively understanding the evolutionary mechanism of the Asian monsoon. In view of the problems existing in present researches of monsoon-dominated climate change at the precession scale, we propose that studies on the environmental significance of geological monsoon proxies, feedback processes in the long-term transient simulations and intercomparisons between observations and modeling results should be strengthened in the future.

precession, Asian summer monsoon, geological record, numerical simulation

Climate change is usually regarded as a result of interactions between the solar radiation arriving at the top of the atmosphere and the coupled atmosphere-ocean-cryosphere-land-biosphere climate system. Variation in the solar radiation is often considered as the primary forcing, though amplitudes and phases of climatic responses on different spatiotemporal scales might be regulated by various physical, chemical and biological feedbacks in the complex system. According to Milankovitch theory of ice-age cycles[1], the periodical variation in the insolation controlled by Earth's orbital parameters is the main driver to the global ice volume changes on the orbital scale. In the past 30 years, studies on geological observations and numerical simulations have been largely promoted with the rapid developments of geological chronology, isotope measurement and computing technique. A lot of geological records from oceans, loess deposits, ice cores and cave speleothems indicate significant cycles in the climate evolution, which are consistent with the orbital periods including precession, obliquity and eccentricity[2,3]. The 23 ka and

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41 ka cycles are usually considered respectively as linear responses of climate system to precession and obliquity[4]. But the generating mechanism of 100 ka cycle is more complicated and till now debates still exist[5]. Research progress and existing questions on the Milankovitch theory can be found in recent reviews[6,7].

The orbital forcing has also left its footprint in the long-term evolution of the Asian monsoon as revealed in the geological records[8,9]. However, the 100 ka variation in insolation forcing due to eccentricity change is very small and the obliquity forcing merely controls the insolation variations at high latitudes[10–12]. Taking into account the fact that it is precession who remarkably affects the climate in the low latitudes, especially the monsoons, while the physical mechanism is still unclear, here we systematically review studies relevant to the past development course, presently existing debates and future research directions for the effect of precession on the Asian summer monsoon.

1 Precession and its effect on the insolation variation

Precession refers to the continuous change of rotational axis during the revolution of the earth. As early as about 200 BC, one astronomer from ancient Greece discovered this phenomenon and 300 years before now Newton first explained how the precession comes into being. The earth rotates by its axis during its revolution around the sun. Owing to the cooperation of the imbalanced gravity from the sun and moon, the earth axis wobbles and moves in a circle around the ecliptic pole with an angular radius of about 23.5°. The shift of equinox is 1° in 76 years and the whole cycle equals 25700 years. Figure 1 shows that, if the summer solstice is located at the perihelion, which means that the seasonal contrast of isolation is strengthened, the winter solstice will occur at the perihelion after half period of precession with decreased seasonal contrast. It is the effect of displacement of the equinox that leads to a difference of about 20 minutes between a solar year and a sidereal year and so is called "lunisolar precession". Besides, the earth is also influenced by the gravity from other planets, which may also make the change of ecliptic plane and the displacement of equinox, thus resulting in the "planetary precession". However, the planetary precession is much smaller and usually equals about 1% of the lunisolar one. Generally, the word "precession" we mentioned is actually the sum of them.

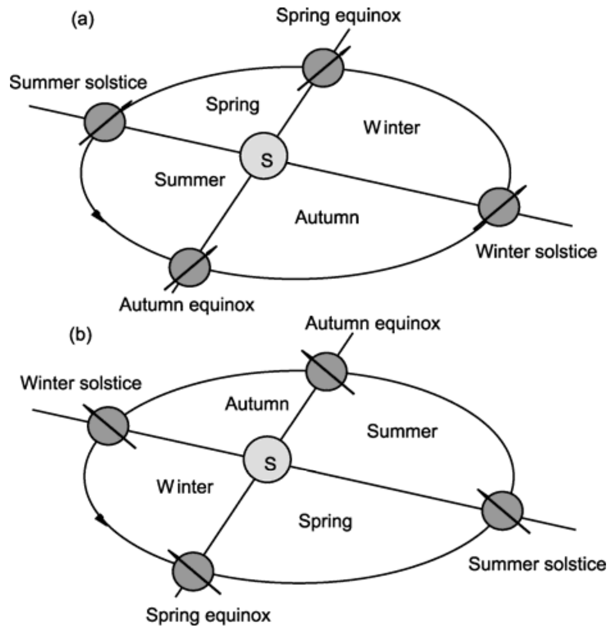

Figure 1 Sketch map for a precession cycle of the earth. The summer solstice (a) or winter solstice (b) is located at the perihelion. The circles represent respectively the earth and sun (S).The seasons are defined according to the Northern Hemisphere.

The precession in the paleoclimate studies, especially in the Milankovitch theory, is a little different from the astronomical precession. The reference point of climatic precession is not fixed but is relative to the perihelion impacted by the axial wobbling. So the period of climatic precession is between about 19000 and 23000 years, as an average of 21700 years, not equal to the astronomical one[3]. Precession, obliquity and eccentricity, as three parameters of the Earth's orbit, control the distribution of solar radiation at the top of atmosphere (insolation). The widely used algorithm and values of insolation on the orbital scale now are obtained by Berger et al.[10,11] on the basis of previous researches. The parameter of precession is defined by $p=e^{*}\sin(\omega)$, in which e is eccentricity and ω is the longitude of the perihelion. As shown in Figure 2, during the past 300 ka, the precession parameter varies between −0.05 and 0.05, which is regulated by changes in eccentricity (0.0125—0.0503). The seasonal contrast of insolation is remarkably influenced by precession and the effect is actually inverse in different hemispheres. Hence, maximal summer insolation occurs together with minimal winter insolation in the NH (Figure 2(b),(c)) when the precession parameter is minimal (Figure 2(a)). Meanwhile, SH summer (winter) radiation reaches maximal (minimal) when the precession parameter is maximal (Figure

2(d),(e)). Although the insolation changes at different latitudes indicate significant precession cycles as the power spectrum analyses shown (Figure 2(f)—(j)), the most notable effect of precession appears in the low latitudes while obliquity mainly affects the high-latitude climate change[12]. For example, at 30°N, the insolation variation induced by precession can reach 120 W/m^2, accounting for nearly 96% of the total change. In contrast, obliquity-band variation of insolation can only explain 2%. While at 60°N, the effect of precession is reduced to 100 W/m^2, 79% of the whole variability, and obliquity becomes more important. As global monsoons are mainly located in the low latitudes, precession does play a vital role in the monsoon evolution. Additionally, the eccentricity-related 100 ka period is not so obvious since the insolation variation in this band is only about 2 W/m^2, far less than that in precession or obliquity band. According to the calculation of Berger and Loutre[11], the orbital parameters including precession have had stable cycles since late Cenozoic.

2 Geological evidence of precession cycles in the Asian monsoon climate change

With the development of technology for geological field drilling, laboratory analyses and paleoenvironmental reconstructions, more and more long-term climatic proxies show that precession periods exist in the past climate change, especially the monsoon evolution. The precession cycles in monsoon evolution were first recognized through the high lake level records in Africa, Arabia and India during 10—5 ka BP[13]. Previous studies revealed the quasi-20 ka cycles in the African lake areas[14], eastern Mediterranean sapropels[15], Nile River flood fluctuations[16] which reflected the African monsoon intensity. An “African Humid Period” was demonstrated during the early-mid Holocene[17]. The evidence is consistent with the fact that the northern insolation reaches the maximum at 11 ka BP in the last precession cycle. From a long-term view, the precession component was much more significant than other orbital components in the early Pliocene before the formation of the NH glaciations[18].

Various physical, chemical and biological proxies (e.g., aeolian dust flux, organic carbon content, planktonic and benthic foraminifers) in the sediments from the tropical Indian Ocean and Arabia Sea are usually considered as indicators of the intensity of the South Asian monsoon. The upwelling led by strong summer monsoon controls ocean primary productivity and promotes the flourishing

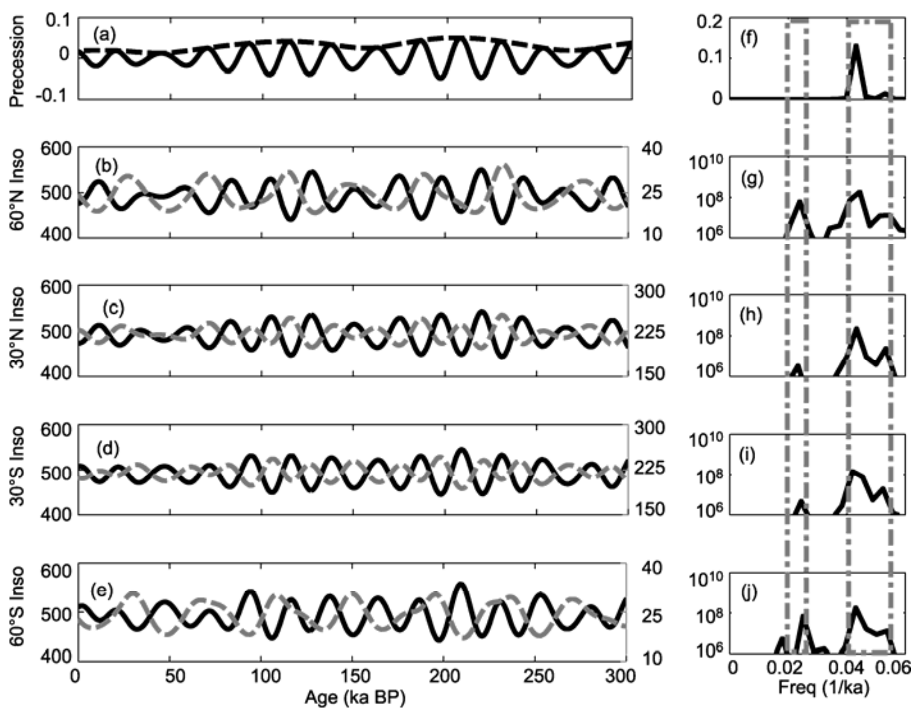

Figure 2 Variations in the insolation induced by perturbations of orbital parameters during the last 300 ka. (a) Parameters of precession (solid line) and eccentricity (dashed line); (b) 60°N insolation for summer (June in NH and December in SH, solid line, left-*Y* axis) and for winter (December in NH and June in SH, dashed line, right-*Y* axis); (c)—(e) same as (b) but for 30°N, 30°S and 60°S, respectively; (f)—(j) Power spectrums of the sequences shown as solid lines in (a)—(e), the dashed rectangles indicate the precession (right) and obliquity (left) bands. The insolation is calculated after Berger and Loutre[11].

of particular species of animals and plants in the northern Indian Ocean. Hence, monsoon activities and their seasonal characteristics have been saved in the fossil records. Biological proxies from oceans[19–21], multi-proxy stacks[22] and continental lake deposits[23] from southwestern China all reflect significant precession cycles in the evolution of South Asian monsoon. Similar with the African monsoon, the precession component was also remarkable in the early Pliocene[24].

The Chinese loess-paleosol sequences are good information carriers for East Asian monsoon evolution as terrestrial deposits. The loess magnetic susceptibility[25–27], calcium carbonate content [28] and snail fossil[29] reflecting the summer monsoon intensity all reveal evident precession cycles. In the grain size records of loess sequences as the indicator of winter monsoon strength[30–32], precession cycles still exist, though they are relatively weaker. Obvious precession signals were also found in the ice cores, lake levels and vegetation records from the Tibetan Plateau[33], and moreover registered in the oxygen and carbon isotope compositions of foraminifera, opal and pollen records[34–36] and geochemical proxies[37] from the South China Sea, as well as pollen records from the Lake Biwa in Japan[38] and the northwestern Pacific Ocean[39]. Recent researches on the reconstruction of the Asian monsoon history using stalagmite sequences from caves, which have absolute chronology and high time resolution and long duration, develop very rapidly. The stalagmite records from Hulu, Sanbao and Dongge caves respectively have revealed the monsoon rainfall variations during the past, 160 ka, 224 ka, 75 ka[40–42], showing dominant precession cycles.

Due to the inverse effect of precession on the insolation changes in the NH and SH (Figure 2), the 20 ka components of monsoon responses in low latitudes of both hemispheres should be opposite. Taking variations of the Asian[40,41] and South American monsoons[43] indicated by absolute-dated stalagmite records during the past 120 ka as an example, we can observe a clear anti-phase relationship between NH and SH monsoon variations at the 20 ka precession band (Figure 3). Similarly, researches with the mountainous ice cores[44] display that the variations of monsoon precipitation or ice volume in different hemispheres were also asynchronous since the last glaciation. The evidence strongly implies the dominance of precession in controlling the monsoon evolution.

3 Numerical simulations on the response of Asian monsoon to precession forcing

The paleoclimate simulations, which are promoted by

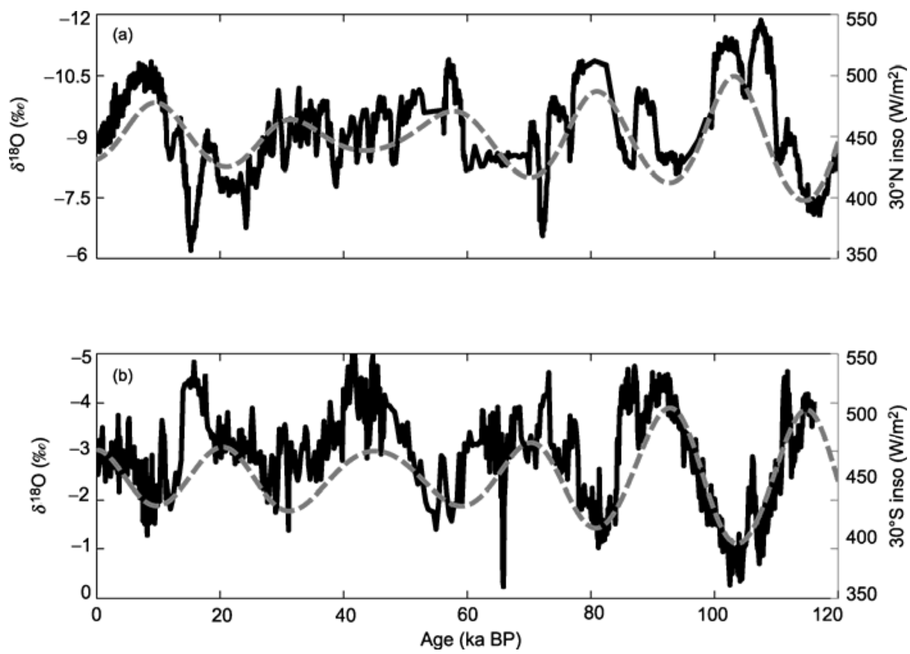

Figure 3 Comparisons between NH and SH orbital-scale monsoon proxies. (a) Stalagmite δ^{18}O record in Sanbao and Hulu Caves, China[41]. Dashed line indicates northern mean summer (June-July-August) insolation at 30°N; (b) stalagmite δ^{18}O record in Brazil[43]. Dashed line indicates southern mean summer (December-January-February) insolation at 30°S. The insolation is calculated after Berger and Loutre[11].

rapid development of computing technique and global climate models, provide direct verification for the "cause and effect" relation between precession and monsoon. The evolutionary mechanism of the Asian monsoon was first proposed by Kutzbach in 1981. Employing an atmospheric general circulation model (GCM) with low resolution, he simulated the Holocene monsoon under setting orbital parameters at 9 ka BP. The increase in northern summer insolation induced by precession enhanced the land-ocean temperature contrast, and then led to a strong Asian-African monsoon and intensified rainfall 9 ka ago, consistent with geological records already obtained. According to this result, Kutzbach proposed that the tropical/subtropical monsoons were driven by orbitally-forced northern summer insolation[45]. Since this three-page pioneering article was published in *Science*, the forcing mechanism of orbital-scale variations in the Asian monsoon has attracted more and more attention and been increasingly deeply studied by Quaternary scientists.

In the recent twenty-odd years, ever-increasing computer capacity has advanced the numerical simulations of the Asian monsoon evolution. In early experiments, GCMs could only be integrated for a few years[45] with the restriction of computer capability, moreover, sea surface temperature (SST) and land surface albedo were usually prescribed, and even the seasonal cycles were neglected[46]. Then the mixed layer[47] or dynamic ocean models[48] and the land surface models[49] were stepwise coupled into atmospheric GCMs. Paleoclimate Modelling Intercomparison Project (PMIP)[50,51], which contains nearly twenty climate models, and other studies[48–53] focus their attentions on the mid-Holocene or other interglacials[54,55] to explore the monsoon response to precession forcing. These experiments demonstrate that precession-induced insolation change is the primary cause for the 20 ka cycles in the summer monsoon evolution.

In addition to the crucial role of precession, the orbital-scale monsoon evolution is also influenced by other feedbacks, in which mechanisms are very complicated. In the simulation by Kutzbach and Geutter[46], for example, 7% increase in July insolation for northern low latitudes at 9 ka BP is associated with 11% higher net radiation at the surface due to increased evaporation and higher water vapor levels in the atmosphere. Feedbacks of land vegetation covers may also modify the monsoon response, which varies with regions and seasons[56]. Liu et al.[48,57] simulated the monsoon evolution during Holocene using a fast ocean-atmosphere model (FOAM) and indicated that the ocean feedbacks were distinct in different monsoon regions, which might be negative for the Asian monsoon. Besides, some experiments[58,59] suggested that the tectonic uplift of the Tibetan Plateau could amplify the orbital-scale variability of Asian monsoon.

The paleoclimate simulation can not be separated from geological evidence. The comparison between model and observation would help understand the history of climate change and more importantly realize the dynamic mechanisms of climate system. Such a typical example is the Cooperative Holocene Mapping Project (COHMAP), a multidisciplinary research of global climate change during the past 18 ka through a combination of climate reconstruction and simulation[60]. In the past, it was impossible to perform a long-term transient paleoclimate simulation with a GCM due to the restriction of computing resource, thus the "time-slice" or "snapshot" simulations were usually conducted for specific periods instead. To realize a comparison with geological sequences, Kutzbach and Geutter[46] conducted a series of time-slice experiments during the past 18 ka with a 3 ka interval under the frame of COHMAP. Their results showed that the response of the Asian monsoon circulation and precipitation is more significant to the precession-induced insolation than to glacial boundary conditions. On the basis of the monsoon precipitation sequences reconstructed with results of time-slice experiments, Prell and Kutzbach[61] pointed out that four strongest South Asian monsoon periods consistently matched four maxima of northern summer insolation during the last 150 ka.

One of the remarkable progresses in the paleoclimate simulation studies is the attempt of the long-term transient simulation with GCMs, which profit from the speedy development of computer technology. Long-term transient runs can reveal the continuous response of climate system to the external forcings and obtain the sequences for comparisons with climatic proxies, thus being superior to time-slice experiments. Previous transient runs usually employ the simple energy balance models (EBMs)[62] or earth system models of intermediate complexity (EMICs)[63,64]. Until recently, long-term transient simulations with GCMs have not been realized. For example, Max-Planck Institute of Meteorology has performed an millenarian experiment employing a coupled ocean-atmosphere model[65]. However, it is still unreasonable for us to run a GCM for as long as thousands of years to test the response of monsoon systems to orbital forcing. In this case, therefore, an orbital accelerating scheme has now emerged[66,67].

With this scheme, Jackson and Broccoli[66], Lorenz and Lohmann[67], and Timmermann et al.[68] respectively simulated the climate change during the last 7 ka, 142 ka and 165 ka. And more recently, Kutzbach et al.[69] set the accelerating factor as 100 and then simulated the response of climate to insolation forcing during the past 284 ka, corresponding actually to 2840 model years. It is so far the longest transient simulation performed with a coupled ocean-atmosphere GCM. There are 12 remarkable precession cycles in the simulated South Asian (25°—27.5°N, 65°—105°E[70]) summer monsoon evolution, which is in phase with the 30°N June insolation (Figure 4). Tuenter et al.[64] designed a 130 ka transient run with an EMIC and their results also indicated the similar in-phase relation between the summer rainfall and precession forcing. Based on the results of an EBM, Short and Mengel[62] found that the African monsoon lags the precession forcing about 3 ka, and the lag time may vary with places due to the thermal inertia difference and for the Asian monsoon region, it is only less than 1 ka. Hence, both equilibrium and transient simulations verify the cause-effect relation between the precession forcing and Asian monsoon variation.

4 Debates on the mechanisms of Asian monsoon variations at the precession band

A number of paleoclimatic proxies and numerical simulations have affirmed the driving effect of precession on the evolution of the Asian monsoon but debates still exist on how the orbital perturbation of insolation affects the monsoon system. With the development of geological reconstructions and model simulations, this question has returned to our vision[71]. Up to now, two contrary hypotheses for the dynamic mechanism have been proposed. First, the “zero phase” theory[71] by Kutzbach[45] indicates that the Asian monsoon is mainly controlled by the northern summer insolation and at most a little phase lag exists between the precession forcing and monsoon response; Second, the “latent heat” hypothesis by Clemens et al.[72] says that in addition to the NH summer insolation, the Asian monsoon is significantly affected by the latent heat transport from the SH.

The “Zero-phase” hypothesis based on a modeling study has been further proved by subsequent many simulations. The recent 284-ka-long transient experiment[69] also clearly shows the nearly zero phase relationship (Figure 4). Above-mentioned various geological evidence, especially the absolute-dating stalagmite record from the caves in southern China[41], indicate the evolution of East Asian monsoon. In warm wet intense-monsoon periods, the values of oxygen isotope composition in stalagmite records are lighter, and *vice versa*. The East Asian monsoon as indicated by stalagmite δ^{18}O records is dominated by the 23 ka period, being consistent with northern summer insolation (Figure 3). These researches provide solid evidence for “zero phase” hypothesis. Actually, due to effect of global ice volume, the maximum of southwestern monsoon lags the insolation about 3 ka on the precession scale[73], which means that “zero phase” is just an approximate.

Ten years later, the proposal of “latent heat” hypothesis became a challenge to the validity of “zero phase” theory. Clemens et al.[22,72] used a 350 ka multi-proxy stack from the Arabian Sea to appeal that on the 23 ka band, the maximum Asian summer monsoon strength lags the maximum NH insolation 125° (about 8 ka), corresponding to the SST minima of southern Indian Ocean. Meanwhile, the ice volume minima lag the northern

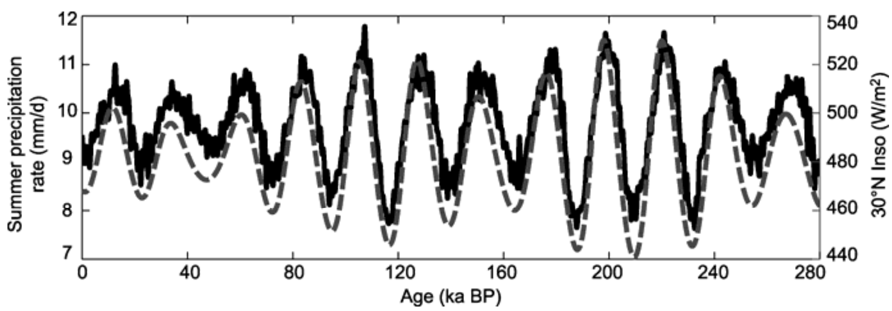

Figure 4 FOAM simulated South Asian summer (JJAS) monsoon precipitation rate (solid line) and 30°N June insolation (dashed line) during the last 280 ka.

summer insolation maxima about 78° (5 ka). Thus, they suggested that only northern summer insolation and ice volume cannot explain such a large phase lag and actually the phase of summer monsoon falls between the minimum ice volume and the maximum northern summer insolation (Figure 5). So they further proposed that the Asian summer monsoon must be largely affected by latent heat transport from the SH, which is controlled by southern summer insolation. Plenty of water vapor is transported to the inland Asia continent through the cross-equatorial air flow and monsoon circulation, eventually strengthening the Asian Low by releasing the latent heat. Records from the Chinese South Sea[75] and Heqing drilling cores[23] both reflected larger phase differences between the Asian monsoon and northern insolation. Moreover, Clemens et al.[76] found that in the Pliocene/Pleistocene the phase of Asian monsoon relative to the ice volume was nonstationary. Before the Quaternary Ice Age, the maxima of Asian monsoon were corresponding to the SH insolation. With the development of glacial cycles, however, the maxima of Asian monsoon tend to start earlier and turn towards the minima of northern ice volume. Hence, the evolution of Asian monsoon system is affected by both external solar forcing and internal climatic feedbacks. Besides, sediment cores from Lake Tanganyika in tropical Africa[77] show the rainfall in the tropical southeastern Africa is highly sensitive to the Asian winter monsoon and the SST of the Indian Ocean during the last 60 ka, that is, mainly controlled by the opposite hemisphere, which can be regarded as another case of the "latent heat" hypothesis outside the Asian region.

Although "latent heat" hypothesis is supported by some observing evidence, it is still very difficult for us to prove its validity through numerical simulations. The influence of southern insolation cannot be excluded because both NH and SH insolation will be altered when the orbital parameters are changed. As a result, the simulated monsoon rainfall is actually affected simultaneously by both hemispheres although it is only consistent with northern insolation (Figure 4). For this reason, Liu et al.[78] designed ideal experiments to explore the response of Asian monsoon by isolating the NH and SH insolation changes. The results show that the northern insolation has a local and immediate effect on the Asian summer monsoon rainfall meanwhile the southern insolation has a remote and seasons-delayed effect. When the southern insolation is strengthened from December

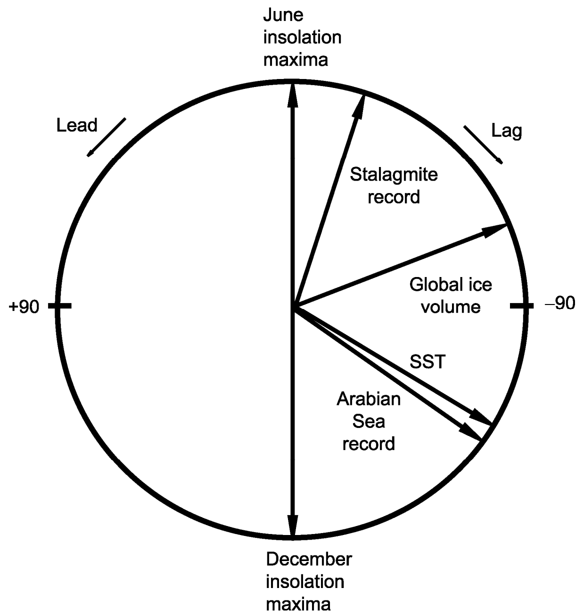

Figure 5 Phase relationships of insolation and monsoon proxies at the precession scale. The clockwise (anti-clockwise) direction indicates phase lag (lead). The phase 0° (180°) means June (December) insolation maximum. The phases of climatic proxies: Stalagmite $\delta^{18}O$ record from South China[41] (−18°); SPECMAP global ice minimum[74] (−78°); R17-98 SST minimum in the southern Indian Ocean[22] (−123°); summer monsoon multiproxy stack from the Arabian Sea[22] (−125°).

to April, the SST rises in the southern Indian Ocean during January to July and then the water vapor increases by promoting evaporation above southern Indian Ocean. Along with the onset of the summer monsoon circulation, more water vapor over southern Indian Ocean is transported northward through the cross-equatorial flow (Somali jet) in the low troposphere, finally enhancing the Asian monsoon rainfall. This implies that the Asian monsoon is actually remotely influenced by southern insolation.

Recently, the "latent heat" hypothesis has begun to be fiercely queried. Although he found a 6 ka phase lag of proxies from the northern Arabian Sea with respect to the early-summer insolation as Clemens et al.[72] did, Reichart et al.[21] attributed such a large phase lag to a regional productivity response to late summer insolation forcing rather than latent heat export from the SH. In a short comment published in 2006, Ruddiman[71] pointed out that high-resolution stalagmite records provided solid evidence to solve the controversy between the two hypotheses. The summer monsoon precipitation variation indicated by the stalagmite-recorded oxygen isotope lags the June insolation by only about 18° (Figure 5), therefore it strongly supports Kutzbach's "zero phase" theory. Meanwhile, he also questioned whether the proxies from ocean deposits could reflect the real changes in the Asian monsoon. Later, Clemens and Prell[79] responded quickly and argued that in Kutzbach's early experiments atmosphere-only models were used and the SST and land surface characteristics were prescribed so that the feedbacks from ocean and vegetation were neglected. They asserted that their oceanic proxies are no doubt as indicators of the Asian monsoon, in which the grain size reflects the wind strength and is independent of other marine upwelling records. Further, they thought that it was unreasonable for Ruddiman et al.[80] to tune the CH_4 records from Antarctic ice cores to 30°N July insolation under "zero phase" hypothesis because CH_4 concentration is not totally controlled by the monsoon-induced tropical wetlands changes. After these arguments, Wang et al.[41] recently published the long-term absolute-dated stalagmite record with a high resolution and confirmed again that the Asian monsoon is nearly in phase with northern summer insolation, which pushed "latent heat" hypothesis to the edge abandoned. But on the American Geophysical Union 2008 fall meeting, Clemens et al.[81] still argued that the stalagmite record might be the indicator of the mixture of summer and winter monsoons instead of summer rainfall. It seems that the debates on the mechanism of Asian monsoon variation will remain.

5 Several issues worthy of in-depth studies

As discussed above, in the last twenty-odd years, our knowledge about the response of Asian summer monsoon to precession forcing has been improving, however, the dynamic mechanism how precession affects the monsoon system remains controversial. To better understand the Asian monsoon evolution and improve the orbital forcing theory, we propose the following several issues worth studying further in the future.

The physical significances of the geological climate proxies should be well clarified. At present some indicators of monsoon intensity and precipitation have been doubted. For example, whether the stalagmite oxygen isotope record indicates the local summer precipitation[41] or mixing information of winter and summer monsoons[81] is still unclear. The Asian monsoon rainfall may not be controlled merely by the wind strength[78], even if grain size records from sediments of the Arabian Sea can reflect the ocean upwelling and monsoon intensity[22]. Only to deeply know the validity and limitation of monsoon proxies can we correctly understand the above phase lag and forcing-response relationships between insolation and monsoon.

The transient model simulations on the orbital scale need to be improved. Although the recently-finished 284 ka transient run[69] reveals the insolation-monsoon in-phase relation, the previous experiments[78] with hemispheric insolation forcing partly support the potential and remote impact of southern insolation on the Asian monsoon. Up to now, however, no experiment has successfully simulated such a significant effect[72] of southern latent heat transportation on the Asian monsoon as Clemens et al. suggested. In the 284 ka run, only the solar radiation change induced by orbital parameters is taken into account, and the variation in global ice volume has been neglected. In fact, only when glacial cycles are considered can the unsteadiness of phase relation of the Asian monsoon[76] to ice volume and the validation of "latent heat" hypothesis be truly tested.

Except for the direct effect of solar forcing, various internal dynamic processes and feedbacks should be considered to assess the climate change. Other than glacial cycles, assessments on oceanic feedbacks, the Tibetan snow cover, land surface vegetation and soil moisture are still insufficient. It is needed to pay attention to the effects of greenhouse gases and global carbon cycle on monsoon dynamics at geological timescale. Variation in the atmospheric methane is mainly controlled by the northern monsoon and low-latitude wetlands, so it in turn acts as an important nonlinear amplifier of precession and obliquity forcings[80]. Precession drives the tropical monsoons and then regulates the ocean carbon cycle, even the global climate[82]. The uncertainties of present numerical models mainly result from the limitation of our knowledge about various physical, chemical and biological processes in the climate system and their mathematical descriptions. It may be the key to assessing various feedbacks by modeling studies and making comparisons with geological records to comprehensively understand the orbital-scale monsoon changes.

Relations between monsoon response and insolation forcing of individual month are to be confirmed. On the precession band, obvious phase differences exist between insolations of different months, in which the maximal June insolation is in phase with negative precession parameter (Figure 2) and May insolation leads to June insolation about 30°, equal to 23000/12 = 1900 years. Like the seasonal lag of the climate system to the solar radiation in a annual cycle, similar phase lag exists in a precession cycle (e.g. 3 ka[62,73]). Climate of a specific month is actually controlled by the insolation forcing 1—2 month earlier. Consequently, early-summer insolation is particularly important to the Asian monsoon development[83]. Hence, it should be noted that when discussing the monsoon response, arbitrary choice of the referenced month of insolation may lead to a phase relation without practical physical meaning. Due to its importance, this question will be specially discussed in our subsequent paper.

The interactions in the Asian monsoon system on different timescales are worthy to be further explored. The monsoon evolution revealed by geological climate proxies is actually a result of interactions of multiple factors on different timescales. In this paper, the main focus is only on the summer monsoon response to precession forcing. However, the precession itself is virtually regulated by the 100 ka cycle of eccentricity[3]. At present day, the effect of precession is relative weak due to the low eccentricity. In accordance with the orbital cycle, the global cooling from 6 ka BP would still last for the coming thousands of years[3] if no anthropogenic intervention. However, our earth would enter an exceptionally long interglacial now[84]. Since Industrial Revolution, the human-induced global warming[85] has likely influenced the natural variability of climate including monsoons. Although obliquity mainly affects the seasonality of climate in the high latitudes, its additive effect on other-scale processes could also increase the complexity of the low-latitude climate response to precession[54]. Moreover, the uplift of the Tibetan Plateau might amplify the orbital-scale variation of Asian monsoon[58,59].

Relations of inter-hemispheric climate variations on different timescales should be attached great importance to. Although the "latent heat" hypothesis is still difficult to be completely affirmed at present, the remote effect from the SH cannot be neglected. Actually, relations between climate changes in different hemispheres are not restricted to the orbital scale. For example, on the millenary scale, a climatic seesaw relationship controlled by the northern Atlantic meridional overturning circulation (MOC) occurs in different hemispheres during the last deglaciation[86]. During the glacial-interglacial cycles, the effect from the SH on the Asian monsoon may also have been registered in the Chinese loess-paleosol sequences[87,88]. It should be pointed out that although both precession and MOC are inclined to induce opposite climate changes in different hemispheres, the dynamic mechanisms may be completely distinct. The evolutionary monsoon system is actually affected by various forcings on different timescales. Hence, the thorough researches on the underlying dynamic mechanisms will be the only way of comprehensively understanding the climate change process and ultimately establishing the theory on the Asian monsoon and environment evolution.

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