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Response of Asian summer monsoon duration to orbital forcing under glacial and interglacial conditions: Implication for precipitation variability in geological records

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ABSTRACT

The responses of Asian summer monsoon and associated precipitation to orbital forcing have been intensively explored during the past 30 years, but debate still exists regarding whether or not the Asian monsoon is controlled by northern or southern summer insolation on the precessional timescale. Various modeling studies have been conducted that support the potential roles played by the insolation in both hemispheres. Among these previous studies, however, the main emphasis has been on the Asian monsoon intensity, with the response of monsoon duration having received little consideration. In the present study, the response of the rainy season duration over different monsoon areas to orbital forcing and its contribution to total annual precipitation are evaluated using an atmospheric general circulation model. The results show that the durations of the rainy seasons, especially their withdrawal, in northern East Asia and the India-Bay of Bengal region, are sensitive to precession change under interglacial-like conditions. Compared to those during stronger boreal summer insolation, the Asian monsoon-associated rainy seasons at weaker insolation last longer, although the peak intensity is smaller. This longer duration of rainfall, which results from the change in land-ocean thermal contrast associated with atmospheric diabatic heating, can counterbalance the weakened intensity in certain places and induce an opposite response of total annual precipitation. However, the duration effect of Asian monsoon is limited under glacial-like conditions. Nevertheless, monsoon duration is a factor that can dominate the orbital-scale variability of Asian monsoon, alongside the intensity, and it should therefore receive greater attention when attempting to explain orbital-scale monsoon change.

1. Introduction

In 1981, after modeling the Asian monsoon climate 9000 years ago, John Kutzbach first proposed the orbital monsoon theory, in which he suggested that Asian monsoon evolution is controlled by Northern Hemisphere (NH) summer insolation induced by changes in the Earth's orbit (Kutzbach, 1981). This hypothesis has gained strong support from geological records in the subsequent years (e.g., Rossigno-Strick, 1983; Pokras and Mix, 1987; de Menocal et al., 2000), thus becoming a popular explanation for orbital-scale monsoon variability. But a multi-proxy stack from the Arabian Sea indicated that the Asian monsoon might be roughly out of phase with NH summer insolation and a significant effect from the latent heat transport from the Southern Hemisphere (SH) ocean was revealed (Clemens and Prell, 2003), which is closely related to SH summer insolation. From then on, whether or not the evolution of Asian monsoon is dominated by NH or SH summer insolation on the orbital timescale has remained an open question (Ruddiman, 2006; Liu and Shi, 2009).

Rapid developments in the reconstruction and analysis of cave stalagmite $\delta^{18}O$ records in South China with absolute-chronology, which show synchronous changes in the monsoon response with boreal summer insolation (Wang et al., 2008), could have ended the debate (Ruddiman, 2006). However, the way in which these stalagmite $\delta^{18}O$ changes have been interpreted, i.e. based on summer monsoonal precipitation or the ratio of summer to winter monsoon

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intensity or some others, has been questioned by modern climatological data analyses (Dayem et al., 2010; Clemens et al., 2010). Over southeastern China in particular, precipitation is not concentrated in summer; winter rainfall also exerts a comparable portion of influence, making it difficult for the stalagmites in this region to be used as purely a reflection of summer monsoon changes at different timescales (Clemens et al., 2010). Thus, we still should not exclude the possibility of southern insolation playing a role in the control of the Asian monsoon variability.

As an important tool in testing the sensitivity of the climate system, and following Kutzbach's pioneer work (Kutzbach, 1981), many modeling experiments have been conducted to explore the response of Asian monsoon to orbital variation. Unfortunately, however, all model experiments, sensitivity runs, or transient runs, whether using atmospheric or coupled ocean-atmosphere models, produce similar results insofar as the northern and southern monsoon systems are significantly intensified as summer insolation increases over the corresponding hemisphere (Liu et al., 2004; Tuenter et al., 2005; Kutzbach et al., 2008). Although the remote impact of southern insolation on the Indian monsoon has been shown to be is of importance (Liu et al., 2006), the large phase lag of the Asian monsoon response on the precession scale, i.e. the "SH latent heat" hypothesis, was proving difficult to simulate, even in a 650-kyr transient run forced by all boundary conditions (Weber and Tuenter, 2011). Furthermore, in an isotope modeling study at around the same time (Pausata et al., 2011), the significance of stalagmite $\delta^{18}O$ was again questioned since it was considered the result of monsoon circulation and not precipitation.

The control of summer precipitation over Asia by southern insolation was firstly captured over northern East Asia (Shi et al., 2012) in a 280-ka-long transient simulation (Kutzbach et al., 2008). The in-phase variation in the precipitation was not a direct response to southern insolation, but one facilitated by a feedback mechanism involving sea surface temperature (SST) over the tropical Pacific Ocean. Forced by orbital change only, the eastern tropical Pacific SST presented synchronous behavior with precession, resulting in stronger East Asian summer monsoon during southern insolation maxima via Pacific-East Asia teleconnection (Shi et al., 2012). The importance of internal ocean feedback in the response of Asian monsoon has subsequently been supported by another transient modeling study, in which an isotope module was enabled (Caley et al., 2014). Under full boundary conditions, regional differences in the Asian monsoon areas induced by tropical SST change were also detected. Furthermore, it was pointed out that stalagmite $\delta^{18}O$ is not a proxy of monsoonal precipitation on the orbital timescale. Thus, ocean feedback might be one of reasons why we have observed inconsistent response of Asian summer monsoon in geological records.

In the present study, we focus our attention on another potential factor not previously mentioned. Traditionally, in earlier studies, the emphasis has been on the response of summer monsoon intensity, i.e. the June–August (JJA) or July precipitation is chosen as an indicator of summer monsoon (e.g., Kutzbach, 1981; Liu et al., 2004; Kutzbach et al., 2008; Weber and Tuenter, 2011). Meanwhile, most of the time, monsoon proxies do not merely reflect the rainfall intensity, but are also influenced by the integrated effect of precipitation amounts. This choice of monsoon intensity fails to include the potential role of summer monsoon duration, which might be important in Asian monsoon change. This potentially important aspect is primarily based on "Kepler's second law (Kepler, 1609)", in that a closer pass of the Earth by the Sun must be faster, i.e. the duration of the summer/summer half-year is shorter when the intensity of incoming summer solar radiation is greater (Berger and Loutre, 1994). When the summer solstice occurs at the aphelion, minimal insolation in boreal summer induces weaker Asian monsoon intensity, but the increased insolation in transitional months might lead to an early onset/late withdrawal of the monsoon season.

Following this idea, we conducted a set of experiments using an atmospheric general circulation model to evaluate the sensitivity of rainy-season duration to orbital change, and also its contribution to the response of total annual precipitation. The responses of monsoon duration under both interglacial and glacial boundary conditions are considered in order to assess the additional role of global ice sheets.

2. Experiments and methods

The model used in our study was the National Center for Atmospheric Research (NCAR) Community Atmosphere Model, version 3.1 (CAM3.1) (Collins et al., 2004). The model was coupled to an ocean surface with prescribed monthly temperature and sea ice taken from HadISST/Reynolds data and the Community Land Model 3 (CLM3) over land. To evaluate the response of Asian monsoon to insolation change induced by astronomical parameters, two control experiments based on the present-day and Last Glacial Maximum (LGM) boundary conditions, respectively, as well as two sensitivity experiments with only precession values changed are designed. The different precession values correspond to the conditions of higher and weaker northern summer insolation, and allow the climate model to test its sensitivity to the insolation change. In detail, two experiments, PSIG and PWIG, were conducted that corresponded to cases with the longitude of perihelion of 282.04° (smaller precession and stronger northern summer insolation) and 102.04° (present-day value, larger precession and weaker northern summer insolation) under interglacial-like conditions, respectively. In terms of the other interglacial boundary forcings, the atmospheric greenhouse gas concentrations were set to pre-industrial values, and all other conditions were kept as they are at present (e.g. tilt, eccentricity, ice sheet cover). Another two experiments, PSG and PWG, were conducted under glacial-like conditions in which the major boundary conditions of the LGM were used. The longitudes of perihelion in PSG and PWG are 294.42 (smaller precession and stronger northern summer insolation) and 114.42 (LGM value, larger precession and weaker northern summer insolation), respectively. The coverage and topography of ice sheets were from the ICE-5G dataset (Peltier, 2004), and the CO_2 concentration was set to 180 ppmv. The tilt and eccentricity were set to their 21ka BP values due to our purpose. Thus, the PWIG and PWG experiments could be considered as the present-day and LGM control runs, respectively. Further details of all the experiments are listed in Table 1. Each run was integrated without flux adjustment, for a period of 15 years, at a horizontal resolution of $2.8^\circ \times 2.8^\circ$ and with 26 vertical levels. The pentad mean outputs for the last 10 years were averaged and analyzed.

Because of differences in duration of the rainy season, the Asian monsoon area was divided into four parts: Arabian Sea (AS: 50°–65°E, 10°–25°N), South Asia (SA: 65°–100°E, 10°–25°N), northern East Asia (NEA: 105°–130°E, 33°–40°N) and southern East Asia (SEA: 105°–130°E, 20°–33°N) (Fig. 1a). Based on their individual periods, it can be seen that both the Indian and East Asian summer monsoon lead to a phased shift in the rain belt between regions. This shift of the rain belt indicates asynchronous rainfall seasonality in both the Indian and East Asian monsoon regions. At present (corresponding to the interglacial-like period with lower boreal summer insolation), the monsoonal rainfall over the Indian monsoon area is concentrated from mid-May to mid-June over the AS (Fig. 1b), shifting to SA as the Indian monsoon develops, and dominating SA in summer and autumn (Fig. 1c). The East Asian summer monsoonal rain belt also exhibits a similar shift