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Transient simulation of the Tibetan Plateau modulated distinct orbital-scale precipitation variation in East and South Asia

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ABSTRACT

The insolation change caused by the Earth's orbital forcing is known to play an important role in regulating variations of the Asian monsoon at various time scales. Geological records and numerical simulation revealed that the climate change in the Asian monsoon region was in-phase or out-of-phase with the boreal summer insolation at the orbital scale. Using the Community Climate System model version 3 and the orbital acceleration technique, we conducted two long-term transient simulations with and without the Tibetan Plateau (TP) orography (TP1 and TP0 experiments). The main objective of this study was to examine the influence of the TP uplift on the orbital-scale precipitation in East and South Asia, and the anti-phase relationship between southern and northern East Asia (SEA and NEA), during the past 150 kyr. The results further confirm that the uplift of the TP significantly affects the Asian atmospheric circulation and precipitation, and is an amplifier of the Asian summer monsoon at the precessional scale. In general, the presence of the TP causes the rain belt and atmospheric circulation front to shift northward. In particular, we found that the anti-phase relationship of precipitation between NEA and SEA at the precessional band is also controlled by the uplift of the TP. Simulations in TP1 and TP0 experiments show that the inverse variations in atmospheric circulation, including the 850 hPa wind field and vertical pressure velocity caused by the uplift of the TP, can directly lead to the out-of-phase JJA precipitation at the precessional scale between NEA and SEA. Future research to collect various climatic proxies with high spatial and temporal resolutions, at least since the Cenozoic, is required to support the simulation results of this study.

1. Introduction

The solar radiation at the top of the atmosphere is one of the primary sources of the Earth's energy, and strongly influences the climate change at various time scales (Rind, 2002). According to the Milankovitch's theory, the insolation is affected by the Earth's orbital parameters (i.e., eccentricity, obliquity, and precession), and leads to quasi-periodic variations in climate.

Many geological studies have indicated that the 100, 40, and 20 ka orbital periods corresponding to the eccentricity, obliquity, and precessional cycles are present throughout the Quaternary climatic evolution. In the Asian monsoon region, the Chinese loess-paleosol sequences (Sun and An, 2005), cave stalagmites (Wang et al., 2008; Cheng et al., 2016), lacustrine and marine sediments (Wang et al., 2005; An et al., 2011) all have 100, 40 or 20 ka orbital periods. Moreover, the Asian monsoon has an obvious precession cycle (Clemens et al., 2008; Wang et al., 2008; Shi et al., 2012) due to its dominant response to daily insolation anomalies caused by the earth orbital parameters changes (Clemens and Prell, 2003; Wang et al., 2008; Li et al., 2013; Liang et al., 2013).

During the past four or five decades, the driving mechanisms and influential processes of the Asian monsoon related to the orbital forcing have received widespread attention. In particular, the introduction of the orbital acceleration technique (Jackson and Broccoli, 2003; Lorenz and Lohmann, 2004) in climate models has made it possible to reveal the long-term changes of the Asian monsoon under orbital forcing and the phase relationships between the Asian monsoon and orbital forcing at long timescales (Kutzbach et al., 2008; Li et al., 2013; Liu et al., 2014; X.J. Zhang et al. 2015). For example, Chen et al. (2011) demonstrated that the southern (northern) part of East Asian summer monsoon (EASM) was in-phase (anti-phase) with the Indian summer monsoon (ISM) at the obliquity band based on a 284,000-year long transient simulation. In accordance with the 284,000-year long transient simulation, the geological records also revealed a reverse phase relation on the precession scale between northern and southern monsoon precipitation (Shi et al., 2012). The land–ocean thermal contrast between Eurasia and its adjacent oceans at the precessional band was pointed out in a 46-kyrs's transient simulation (Wang et al., 2012, 2016). Using a high-resolution long-term transient simulation, Li et al. (2013) found that there were strong signals of the 20 ka precessional cycles in the annual

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precipitation in both monsoonal East Asia and arid central Asia, which varies in-phase with the Northern Hemisphere (NH) summer insolation. However, the mechanism of these in-phase or out-of-phase relationships over the Asian sub-regions at the precessional band remains unclear and the subject of debate.

The Tibetan Plateau (TP), known as the "the roof of the world", is a product of the collision of the Eurasian Plate with the Indian Plate (Molnar et al., 1993; Yin and Harrison, 2000), with an average altitude of over 4000 m and an area of 2.5 million km^2. The TP has a profound impact on Eurasian climate patterns and there are ongoing debates regarding the thermal and mechanical nature of the mechanisms involved (Chen et al., 2014; Boos, 2015). Most of the geological records from Chinese loess show that the TP uplift is closely related to the formation and development of the Asian summer monsoon (ASM) and inland aridification (e.g., Ruddiman et al., 1989; Molnar et al., 1993; An et al., 2001; Guo et al., 2002). In recent years, with the development of numerical modeling and computer technology, a growing number of scientists have conducted a variety of simulation tests related to the TP uplift and have realized great achievements (e.g., Prell and Kutzbach, 1997; Boos and Kuang, 2010; Wu et al., 2012; Boos and Kuang, 2013; Liu et al., 2015; Li et al., 2016). An exciting conclusion is that the TP is an amplifier of orbital-scale variability of the EASM (Prell and Kutzbach, 1997; Liu et al., 2003), which is supported by the geological records (An et al., 2001; Sun and An, 2005).

The following research questions are considered in the current study. Firstly, what is the role of the TP on Asian climate at the orbital scale? Secondly, are these in-phase or anti-phase relationships in precessional bands over the Asian monsoon also related to the TP uplift and if so, what are the underlying physical mechanisms responsible for these? This paper synthetically considers the TP uplift and Earth's orbital forcing, and focuses on analyzing the influence of the TP uplift on orbital-scale precipitation in East Asia and South Asia using two long-term transient experiments with and without the topography of the TP.

2. Numerical model and transient experiments

This study employed the Community Climate System Model version 3 (CCSM3) released by the National Center for Atmospheric Research (Collins et al., 2006). CCSM3 is a global, coupled ocean–atmosphere–sea ice–land surface climate model that has been widely used for past, present, and future climate research. In recent years, CCSM3 has come to the attention of paleoclimate researchers, especially the long-term transient simulations (Li et al., 2013; Liu et al., 2014; Wen et al., 2016). The atmospheric model is the Community Atmospheric Model 3 (CAM3) with 26 hybrid coordinate levels in the vertical and approximately 2.8° resolution in the horizontal. The land model is the Community Land Model (CLM) with the same resolution as the atmosphere, and each grid box includes a hierarchy of land units, soil columns, and plant types. The ocean module is the Parallel Ocean Program (POP) with a nominal horizontal resolution of $1^\circ \times 1^\circ$ and a vertical z-coordinate with 40 levels. The sea ice module is the Community Sea Ice Model (CSIM) with identical resolution to that of the POP.

We conducted two long-term transient experiments for the last 150 kyr using CCSM3 and the orbital acceleration technique (Jackson and Broccoli, 2003; Lorenz and Lohmann, 2004). The first was the TP1 experiment in which using the fixed orbital parameters at 150 ka, the CCSM3 was applied to generate an equilibrium simulation for the first 100 years. In the subsequent simulation years, the CCSM3 employed an acceleration factor of 100 (1 model year = 100 calendar years). Thus, the output 1500 model years from the CCSM3 represent the past 150 kyr. All initial and boundary conditions remained in the initial state during the whole integration. The TP1 experiment has previously been used to analyze the impact of the change in insolation caused by the Earth's orbital forcing on precipitation in the monsoonal East Asia monsoon and arid central Asia over the past 150 kyr (Li et al., 2013). The second simulation was the TP0 experiment. The only difference between the TP1 and TP0 experiments was that the terrain altitude over the TP bounded by 60–110°E, 20–40°N was reduced to 10% of present-day. Hence, this study analyzed the two long-term transient experiments with and without the TP (TP1 and TP0 experiments, respectively). It should be noted that the time series data in this study were processed using the 3-kyr moving averages (30 model years) to filter out noise and outliers for easy plotting and interpretation.

3. Responses of the Asian climate to insolation forcing

3.1. Composite analysis

Composite analysis was used to compare the effects of insolation variation of the precessional cycle on precipitation and atmospheric circulation over the Asian region. As in Li et al. (2013), we took the year with the maximum (minimum) of June insolation at 45°N as the central year, and then selected 5 model years before and after the central year. Thus, the average of the seven periods of high (low) insolation was used to represent the high-insolation (low-insolation) phase and was abbreviated as HI (LI) in the composite analysis. Fig. 1A and B show the differences in precipitation rate between HI and LI phases as HI–LI values in both the TP1 and TP0 experiments. In TP1 test, the precipitation intensified over East and South Asia and weakened over central Asia on the HI phase. There were clear distinction between the abundant rainfall in northern East Asia (NEA) associated with the HI phase and the scarce rainfall over southern East Asia (SEA). However, in the TP0 test, almost all precipitation increased over Asia during the HI phase. The difference in the JJA 850 hPa wind field between the HI and LI phases in both the TP1 and TP0 experiments show that the JJA EASM was significantly enhanced and shifted northward (Fig. 1C and D). This is because the JJA 850 hPa wind markedly strengthened in the northern East Asia and northwestern Africa only in the TP1 test. In contrast, the JJA 850 hPa wind increased widely over mid-latitudes in the TP0 test. This suggests that the climate change caused by orbital scale insolation variation over Asia is closely linked to the high TP terrain.

3.2. Long-term variations of precipitation in East and South Asia

Based on the above results, we conclude that the precipitation variations over different sub-regions in Asia are associated with NH summer insolation variations caused by the precessional forcing. Based on the composite analysis, we selected four sub-regions to analyze the long-term variations of the precipitation during the past 150 kyr: NEA (105–125°E, 35–40°N) and SEA (105–125°E, 25–30°N) and the northern (NSA: 70–90°E, 20–25°N) and southern (SSA: 70–90°E, 10–15°N) South Asia regions depending on precipitation and wind field distribution from the results of the composite analysis. Fig. 2A and B show the time series of the simulated JJA precipitation rate in NEA, SEA, NSA, SSA, and the June insolation at 45°N during the past 150 kyr in the TP1 and TP0 experiments. There were remarkable 20-kyr periods in East Asia and South Asia during the past 150 kyr both with and without TP terrain, indicating that the precessional forcing controls the precipitation via its dominant role in the boreal summer insolation (Fig. 2E). Here, we should note in TP1 that the precipitation variation is out-of-phase with the June insolation at 45°N in SEA, but in-phase in NEA (Fig. 2A). When the precession-induced boreal summer insolation increases, the rainfall significantly weakens (intensifies) in SEA (NEA) with contemporary TP terrain. Interestingly, the JJA precipitation variations in both NEA and SEA are synchronous and in-phase with the June insolation at 45°N in TP0 experiment without the TP terrain. Thus, we emphasize that the phase difference of TP0 from the TP1 is modulated by the TP topography which could modify the behavior of the El-Nino/Southern Osillation (ENSO) (Kitoh, 2007) and its influence on the anti-phased response of NEA and SEA JJA precipitation (Shi et al., 2012).

Fig. 2C and D show the long-term precipitation variation in South Asia. Like the East Asia region, there are strong signals of the 20 ka