Earth and Planetary Science Letters 484 (2018) 295–308

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Changes in Tibetan Plateau latitude as an important factor for understanding East Asian climate since the Eocene: A modeling study

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A R T I C L E I N F O

Article history:
Received 7 August 2017
Received in revised form 14 December 2017
Accepted 16 December 2017
Available online xxxx
Editor: M. Frank

Keywords:
surface uplift
Tibetan Plateau
East Asian monsoon
latitude & paleogeography

A B S T R A C T

Previous climate modeling studies suggest that the surface uplift of the Himalaya–Tibetan plateau (TP) is a crucial parameter for the onset and intensification of the East Asian monsoon during the Cenozoic. Most of these studies have only considered the Himalaya–TP in its present location between ∼26°N and ∼40°N despite numerous recent geophysical studies that reconstruct the Himalaya–TP 10° or more of latitude to the south during the early Paleogene. We have designed a series of climate simulations to explore the sensitivity of East Asian climate to the latitude of the Himalaya–TP. Our simulations suggest that the East Asian climate strongly depends on the latitude of the Himalaya–TP. Surface uplift of a proto-Himalaya–TP in the subtropics intensifies aridity throughout inland Asia north of ∼40°N and enhances precipitation over East Asia. In contrast, the rise of a proto-Himalaya–TP in the tropics only slightly intensifies aridity in inland Asia north of ∼40°N, and slightly increases precipitation in East Asia. Importantly, this climate sensitivity to the latitudinal position of the Himalaya–TP is non-linear, particularly for precipitation across East Asia. The simulated precipitation patterns across East Asia are significantly different between our scenarios in which a proto-plateau is situated between ∼11°N and ∼25°N and between ∼20°N and ∼33°N, but they are similar when the plateau translates northward from between ∼20°N and ∼33°N to its modern position. Our simulations, when interpreted in the context of climate proxy data from Central Asia, support geophysically-based paleogeographic reconstructions in which the southern margin of a modern-elevation proto-Himalaya–TP was located at ∼20°N or further north in the Eocene.

1. Introduction

The importance of the Himalaya–Tibetan plateau (TP) on global and regional climate has been emphasized in many studies, with particular interest in the climatic impact caused by its elevation change. Thermal and dynamical effects (Boos and Kuang, 2010; Roe et al., 2016) associated with the surface uplift of the Himalaya–TP can intensify Asian inland aridity and the East Asian monsoon (Kutzbach et al., 1989; An et al., 2001; Zhang et al., 2007; Jiang et al., 2008) and also trigger the transition of paleoclimate patterns within China (Zhang et al., 2007; Guo et al., 2008). Climate modeling studies have been able to reach these conclusions in a step-by-step manner over the years. Pioneering studies only considered surface uplift of the Himalaya–TP as a single large physiographic feature, using coarse-resolution climate models, and with only two conditions: full- and no-mountain elevation distributions (Manabe and Terpstra, 1974). A number of subsequent studies modeled the surface uplift of the Himalaya–TP in multiple stages (An et al., 2001; Liu and Yin, 2002; Abe et al., 2003). Recently, more realistic experiments have been carried out with higher resolution climate models by implementing an asynchronous surface

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https://doi.org/10.1016/j.epsl.2017.12.034
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uplift history across different regions of the Himalaya–TP (e.g., Zhang et al., 2012, 2015).

Most of the climate simulations to date only consider the surface uplift of the Himalaya–TP based on its modern position, mainly between ∼26°N and ∼40°N in the subtropics. The southern margin of a proto-Himalaya–TP, however, was located at least partially in the high tropics in the early Cenozoic (Van der Voo et al., 1999; van Hinsbergen et al., 2011; Lippert et al., 2014). In the early stages of the India–Asia collision, from ∼60 to ∼40 Ma (Najman et al., 2010; DeCelles et al., 2014), the southern margin of the proto-Himalaya–TP was located more than 1,000 km south of its present position, with the southern-most latitude of the orogenic system estimated to be at ∼16°N (Lippert et al., 2014; Huang et al., 2015b). The latitude of the northern margin of an Early-to-Middle Eocene proto-plateau is less well understood. Here, we adopt a paleogeography that is a hybrid of those summarized by Wang et al. (2008) and Rohrmann et al. (2012) such that we prescribe the northern boundary of a high (*i.e.*, >3000 m) proto-plateau at ∼40 Ma to be located within the Songpan–Ganzi region (∼36°N in modern coordinates). This implies a minimum north-south width of an Early-to-Middle Eocene high proto-plateau of ∼10° of latitude. Various elevation proxy data suggest that large areas of southern Tibet were at an elevation of ∼4,000–5,000 m by this time (Quade et al., 2011; Searle et al., 2011; Li et al., 2015), and structural, sediment provenance, and thermochronometric data are consistent with the cessation of most crustal shortening within large regions of Central Tibet (*i.e.*, Qiangtang, Songpan–Ganzi, Kunlun) by the end of the Eocene (e.g., Wang et al., 2008; Clark et al., 2010; Rohrmann et al., 2012; Staisch et al., 2016). The paleo-elevation history of the northern TP (*i.e.*, north of the Kunlun) is less certain, but structural and stratigraphic data suggest that many areas were at low or intermediate elevations (≪3000 m) (Tapponnier et al., 2001; Ritts et al., 2008; Yuan et al., 2013). Pollen data from the Xining Basin on the NE margin of the modern TP, however, are consistent with the mountains surrounding this basin at elevations that are similar to their modern heights since ∼38 Ma (Dupont-Nivet et al., 2008). The regional extent of this high topography is unclear, but it could be significant, and structural and stratigraphic records are consistent with crustal shortening within NE Tibet at this time (*e.g.*, Yin et al., 2008; Clark et al., 2010; Zhuang et al., 2011). We do not reconstruct this high topography in NE Tibet in our simulations because our focus is on the 60–40 Ma climate, but we note the importance of incorporating this topography in future simulations and in studies of Late Eocene and younger climate.

The northward motion of the Indian and Asian continents transported the proto-Himalaya–TP gradually northward entirely into the subtropics, and all the while, a variety of lithospheric processes associated with India–Asia convergence enlarged the Himalaya south of the Tibetan Himalaya and north of the Songpan–Ganzi area (Tapponnier et al., 2001; Kapp et al., 2005; Wang et al., 2008), as well as expanded the northeastern and eastern margins of the plateau (Yuan et al., 2013; Li et al., 2014, 2015). We emphasize that the history of the surface uplift of the Himalaya–TP is complex, with the height, extent, and latitudinal position of high elevation regions constrained by only a few key proxy studies. Previous modeling efforts have highlighted the crucial climate impact of the elevation and extent of the Himalaya–TP (Kutzbach et al., 1989; An et al., 2001; Liu and Yin, 2002; Abe et al., 2003; Zhang et al., 2007; Jiang et al., 2008), but only a few studies have accounted for the TP at different latitudes (Huber and Goldner, 2012; Licht et al., 2014).

Here, we use simplified paleogeographic scenarios (Fig. S1) to investigate the climate impact of the northward movement of a proto-Himalaya–TP, which has recently become better constrained (Lippert et al., 2014) relative to the surface uplift history of the Himalaya–TP (Quade et al., 2011), which is also one of the most difficult parameters to constrain (Botsyun et al., 2016). We use the Community Atmosphere Model version 4 (CAM4) (Neale et al., 2013) running with modern and ∼40 Ma boundary conditions to compare the difference in East Asian wind and precipitation patterns between a Himalaya–TP that rises in the tropics and one that rises in the subtropics. We consider the Himalaya and a TP as far north as the Songpan–Ganzi region with modern height, as well as scenarios with intermediate elevations. Most reported geological evidence suggests that these regions were at high elevation by late Eocene if not even earlier (Wang et al., 2008; Quade et al., 2011; Searle et al., 2011; Lippert et al., 2014; Li et al., 2015).

The Asian monsoon includes a tropical and a subtropical subsystem. Because the tropical Asian monsoon influences mainly South Asia, it is often called the South Asian monsoon, whereas the subtropical monsoon affects a region of East Asia that includes China, Mongolia, Korea, and Japan, and it is thus referred to as the East Asian Monsoon. At ∼40 Ma, the boundaries of these regions, including the boundaries of the Chinese mainland and inland Asia, have changed due to plate motion and crustal deformation. Here, we mainly focus on the East Asian climate, which includes the East Asian monsoon climate and inland Asian arid climate and does not include the South Asian monsoon climate. To investigate the sensitivity of East Asian climate to the latitude of the Himalaya–TP, we prescribe three positions of the plateau: high topography located as it is today, between ∼11°N and ∼25°N, and between ∼20°N and ∼33°N. The most southerly latitude range represents a hypothetical end-member paleogeography of the proto-Himalaya–TP, while a high elevation proto-plateau located between ∼20°N and ∼33°N represents an intermediate paleogeography of the proto-Himalaya–TP in the late Eocene (Van der Voo et al., 1999; van Hinsbergen et al., 2011; Lippert et al., 2014). The latitudinal width of our proto-plateau is slightly larger than what we described above to account for some crustal shortening since 40 Ma and uncertainty in the northern limit of high plateau topography. Because of uncertainties in constraining the precise height, extent, and latitude of the Himalaya–TP, here we focus on the sensitivity of East Asian climate to the tropical versus subtropical position of the TP, which is also crucial for understanding the evolution of the East Asian monsoon. It is not our intent to precisely and fully simulate the Eocene climate, but rather to highlight climate sensitivity in an effort to guide future modeling, proxy development, and field studies of the Tibetan Plateau.

2. Model and experimental design

CAM4 is the atmospheric component of the Community Earth System Model (CESM; see the CESM website at http://www2.cesm.ucar.edu/) from the National Center for Atmospheric Research. We used a horizontal resolution of F09, which is the default resolution for many applications (Neale et al., 2013) and which is configured by ∼0.9° in latitude and 1.25° in longitude, with 26 vertical layers. With this resolution, the model uses a finite-volume dynamical core and simulates the large-scale pattern of modern Asian rainfall well (Neale et al., 2013). A detailed description of the model can be found in Neale et al. (2010).

We conducted twelve experiments based on ∼40 Ma and modern land–sea distributions (Table 1 and Fig. S1). Due to the long run time required by using a high-resolution fully coupled model, we use the lower resolution (atmosphere, ∼3.75° and 26 vertical levels; ocean, ∼3° and 32 vertical levels) version of the Norwegian Earth System Model (NorESM-L) as ‘a sea surface temperature (SST) simulator’ and thus our ∼40 Ma experiments entail a two-step process. First, we simulate the ∼40 Ma SSTs by run-