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Do climate simulations support the existence of East Asian monsoon climate in the Late Eocene?

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ABSTRACT

Early synthesis of geologic evidence demonstrated that a zonal climate pattern once dominated China in the Paleogene. The zonal climate pattern is very different from the non-zonal modern monsoon climate pattern. It has been hypothesized that the transition from a zonal to non-zonal pattern is related to the initiation of the East Asian monsoon. The earliest timing of East Asian monsoon initiation is suggested to be the Late Eocene, although this is still the subject of hot debate. Here, we use the low-resolution Norwegian Earth System Model (NorESM-L) and the high-resolution Community Atmosphere Model version 4 (CAM4) to simulate the climate in China for the Early and Late Eocene and further evaluate the climate effect of topography and sea-surface temperature (SST) on East Asian regional climate. Our simulations supported a zonal/zonal-like arid desert/steppe climate band appearance in China in the Early Eocene, but the zonal band very likely disappeared in the Late Eocene due to increased precipitation over East China. The increased precipitation is caused by intensified summer southerlies, associated with the westward extension of the western Pacific subtropical high (WPSH) in the Late Eocene. However, the disappearance of a zonal climate band does not sufficiently indicate formation of an East Asian monsoon climate in the Late Eocene: simulated wind and precipitation seasonality is still much weaker in the Late Eocene and should be distinguished from the modern monsoonal seasonality.

1. Introduction

Modern China is controlled by a typical monsoon climate, showing a non-zonal climate pattern with monsoon-dominated humid/semi-humid regions located in the southeast and arid/semi-arid regions in the northwest. In summer, southeasterlies and southwesterlies (summer winds, also called summer monsoon) penetrate northward and bring abundant moisture to monsoon-dominated regions, while little moisture is transported to inland China. In winter, cold-dry north-westerlies (winter winds, also called winter monsoon) blow over most of northern China.

Before the establishment of the non-zonal monsoon climate pattern, China was dominated by a zonal climate pattern, with a broad arid belts stretching from west to east (e.g., Liu and Guo, 1997; Sun and Wang, 2005; Zhang and Guo, 2005; Guo et al., 2008). It has been hypothesized that the transition from a zonal to non-zonal pattern is related to the initiation of the East Asian monsoon.

However, timing of the monsoon-dominated climate in East Asia is still the subject of hot debate. Well-known Quaternary loess-paleosol sequences record East Asian monsoon history since 2.6 Ma (Heller and Liu, 1984; Liu, 1985; Kukla, 1987; An et al., 1990; Liu and Ding, 1993; Rutter and Ding, 1993; Liu and Ding, 1998). Later, studies of the late Miocene–Pliocene red clay sequences on the Chinese Loess Plateau revealed that East Asian monsoon climate already existed as early as ~7–8 Ma (Sun et al., 1997, 1998; Ding et al., 1999, 2001; An, 2000; An et al., 2001). In 2002, the finding of Miocene loess-paleosol sequences at Qinan, in the western Loess Plateau in central China, pushed the East Asian monsoon history back to at least 22 Ma (Guo et al., 2002, 2008). However, recent studies, mainly based on saline cycles in lake gypsum and dry mudflat red mudstones sediments from Xining Basin, extended the East Asian monsoon history further back to the Late Eocene, ~40 Ma (Licht et al., 2014; Licht et al., 2016).

Due to the paucity of well-dated proxies in Paleogene East Asia, it is meaningful and necessary to investigate the onset of the East Asian monsoon climate in the Eocene from the perspective of paleoclimate modeling. Many modeling studies have investigated Eocene climate, with consideration of climate sensitivity to different greenhouse gases levels (Shellito et al., 2009; Lunt et al., 2010; Winguth et al., 2010),

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high topography (Huber and Goldner, 2012; Licht et al., 2014; Zhang et al., 2015), and land–sea distributions (Huber et al., 2004; Roberts et al., 2009; Zhang et al., 2012b). Among these studies, Zhang et al. (2012b) illustrated that Asia was dominated by a zonal desert and steppe climate, with limited monsoons, during the Early Eocene. Later, modern-like monsoonal rainfall and wind occurred in Late Eocene simulations (Licht et al., 2014), due to a reinforced hydrological cycle responding to enhanced greenhouse conditions.

These modeling efforts suggested a wetter condition over East Asia in the Late Eocene relative to the Early Eocene. These results are generally consistent with geological evidence from paleobotanical analysis, which also support a wetter condition in the Late Eocene relatively to the Early Eocene, with declining proportion of *Ephedripites* in pollen assemblages over East China (Song et al., 1985; Sun et al., 1989; Mao et al., 1995; Tong et al., 2001; Sun and Wang, 2005). However, there are still unanswered questions. First, why the climate tended to be wetter over East China from the Early to Late Eocene? Second, does a wetter condition over East China in the Late Eocene sufficiently indicate the formation of a monsoon climate in East Asia like modern? To answer these questions, we should consider three factors from the perspective of paleoclimate modeling: changes in land–sea distributions, topographic reorganization and atmospheric carbon dioxide concentration (Pearson and Palmer, 2000; Zachos et al., 2001; Pagani et al., 2005). All of these factors varied significantly in the Eocene and could impact Asian climate.

In this paper, focusing on the Eocene East Asian climate evolution, we carry out simulations with two different land–sea distributions for the Early and Late Eocene. We further test the regional climate impacts in East Asia due to changes in land surface topography and SST, induced by modifications in land–sea distribution. With the low-resolution version of the Norwegian Earth System Model (NorESM-L) (Zhang et al., 2012c), we carry out fully coupled simulations for the Early and Late Eocene. Then, with a high-resolution atmosphere-only model, the Community Atmosphere Model version 4 (CAM4), we perform sensitivity experiments to discuss the climate effects of topography and SST.

The following text is organized as follows. Section 2 introduces the model and experimental design. Section 3 presents simulation results. We discuss the simulated wind and precipitation seasonality in the Early and Late Eocene epochs in Section 4 and finally provide a summary in Section 5.

2. Modeling and experimental design

2.1. Model introduction

NorESM-L is an Earth system model based on the Community Earth System Model from the National Center for Atmospheric Research (NCAR). Different from the standard configuration of CESM, the ocean component in NorESM-L is changed to the Miami Isopycnic Coordinate Ocean Model (MICOM), and an advanced chemistry–aerosol–cloud–radiation interaction scheme can be used in the atmosphere component (Zhang et al., 2012c; Bentsen et al., 2013). In NorESM-L, the atmosphere model resolution is T31 (~3.75°) in horizontal, and 26 levels in vertical. The ocean component resolution is g37 (~3°) in horizontal, and 32 layers in vertical. Detailed documentation for each component of the model system has been provided previously (Zhang et al., 2012c; Bentsen et al., 2013). The model performs well in simulating both preindustrial climate and paleoclimate (Zhang et al., 2012c, 2013, 2014; Bentsen et al., 2013).

The higher-resolution CAM4, 0.9° latitude by 1.25° longitude grid, and 26 vertical levels, employs a Finite-Volume dynamical core (a conservative "flux-form semi-Lagrangian" scheme) for horizontal discretization (Lin and Rood, 1997; Lin, 2004), and Lagrangian with a conservative remapping for vertical discretization. CAM4 reasonably simulates the large-scale Asian summer monsoon (Zhang et al., 2012a). The higher-resolution CAM4 better simulates precipitation because topographic effects are better resolved (Shields et al., 2012).

2.2. Boundary conditions and experimental design

2.2.1. Coupled experiments

Global land–sea distributions for the Early and Late Eocene were set following the global paleogeography map database by Scotese (2001) for 50 Ma and 40 Ma, respectively. In the paleogeography map database, mountains, coastlines and shallow ocean basins, and magnetic lines on the ocean floor were outlined. Based on these datasets and following the method outlined by Bice et al. (1998), we reconstructed the land–sea configuration and relief topography and established bathymetric conditions. This method has been presented previously in Zhang et al. (2011, 2014). Coastlines were set at 0 m elevation, and shallow ocean basins were specified as 200 m deep. The depth data of each magnetic line were calculated based on the age-depth relationships built by Bice et al. (1998), and then were interpolated into a global area configuration.

In the Early Eocene, high mountains located in Southern China were set to less than 1500 m above sea level, and the average Tibetan Plateau was specified at 1300 m above sea level. In the Late Eocene, we established a closed West Siberian Seaway, deepened the Arctic-Atlantic Seaway and Drake Passage, and elevated the Tibetan Plateau and Mongolian Plateau to larger sizes.

Other boundary condition in the Early and Late Eocence were kept identical. The solar constant and orbital parameters were set to present conditions. Vegetation conditions on land were idealized in coupled simulations, with forest between 30°N and 30°S and shrub/grass outside this latitude band. Except for atmospheric CO_2 concentration, all other trace gases and aerosols were specified to present conditions.

Four coupled experiments were conducted in total (Table 1). First two experiments simulate the Early and Late Eocene (50 Ma and 40 Ma) climate with representative atmospheric CO_2 concentrations of 1120 and 1050 ppmv, respectively (described as EEOC1120 and LEOC1050 later). For each Eocene simulation, coupled simulations were also performed at doubled atmospheric CO_2 levels (described as EEOC0560 and LEOC0560, respectively). All coupled experiments were run for 2200 yr. The average period of simulation results for climatological analysis is the last 200 yr.

2.2.2. Atmosphere-only experiments

Forced with fixed SST from fully coupled model simulations with doubled atmospheric CO_2 levels (EEOC0560 and LEOC0560), we ran the atmosphere-only model CAM4 to carry out sensitivity experiments (Table 1), with a model resolution of F09, about 0.9° latitude by 1.25°

Table 1
Boundary conditions and experimental design.

NorESM-L coupled experiments			
Experiments	Landsea	Topography	CO_2 (ppmv)
EEOC1120	50 Ma	50 Ma	1120
LEOC1050	40 Ma	40 Ma	1050
EEOC0560	50 Ma	50 Ma	560
LEOC0560	40 Ma	40 Ma	560

CAM4 high-resolution experiments				
Experiments	Landsea	Topography	SST	CO_2 (ppmv)
EEOC0560-CAM4	50 Ma	50 Ma	EEOC0560	560
LEOC0560-CAM4	40 Ma	40 Ma	LEOC0560	560
EEOC0560-CAM4-FLAT	50 Ma	FLAT	EEOC0560	560
LEOC0560-CAM4-FLAT	40 Ma	FLAT	LEOC0560	560
EEOC1120-CAM4-FLAT	50 Ma	FLAT	EEOC1120	1120
LEOC1050-CAM4-FLAT	40 Ma	FLAT	LEOC1050	1050