Quaternary Science Reviews 116 (2015) 1–14

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Impacts of uplift of northern Tibetan Plateau and formation of Asian inland deserts on regional climate and environment

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ARTICLE INFO

Article history:
Received 22 September 2014
Received in revised form
13 March 2015
Accepted 15 March 2015
Available online 2 April 2015

Keywords:
Tibetan Plateau
Tectonic uplift
Asian inland
Desert formation
Mio-Pliocene climate trend
Regional climate model

ABSTRACT

Based on the geological evidence that the northern Tibetan Plateau (NTP) had an uplift of a finite magnitude since the Miocene and the major Asian inland deserts formed in the early Pliocene, a regional climate model (RegCM4.1) with a horizontal resolution of 50 km was used to explore the effects of the NTP uplift and the related aridification of inland Asia on regional climate. We designed three numerical experiments including the control experiment representing the present-day condition, the high-mountain experiment representing the early Pliocene condition with uplifted NTP but absence of the Asian inland deserts, and the low-mountain experiment representing the mid-Miocene condition with reduced topography in the NTP (by as much as 2400 m) and also absence of the deserts. Our simulation results indicated that the NTP uplift caused significant reductions in annual precipitation in a broad region of inland Asia north of the Tibetan Plateau (TP) mainly due to the enhanced rain shadow effect of the mountains and changes in the regional circulations. However, four mountainous regions located in the uplift showed significant increases in precipitation, stretching from the Pamir Plateau in the west to the Qilian Mountains in the east. These mountainous areas also experienced different changes in the rainfall seasonality with the greatest increases occurring during the respective rainy seasons, predominantly resulted from the enhanced orographically forced upwind ascents. The appearance of the major deserts in the inland Asia further reduced precipitation in the region and led to increased dust emission and deposition fluxes, while the spatial patterns of dust deposition were also changed, not only in the regions of uplift-impacted topography, but also in the downwind regions. One major contribution from this study is the comparison of the simulation results with 11 existing geological records representing the moisture conditions from Miocene to Pliocene. The comparisons revealed good matches between the simulation results and the published geological records. Therefore, we conclude that the NTP uplift and the related formation of the major deserts played a controlling role in the evolution of regional climatic conditions in a broad region in inland Asia since the Miocene.

1. Introduction

The Tibetan Plateau (TP), standing in the southern Asian continent (approximately in 25°–40°N, 74°–104°E) and known as “roof of the world”, is the highest plateau in the world, with an area of 2.5 million square kilometers and an average elevation over 4000 m. The TP is bounded by magnificent mountain ranges, such as the Himalayan Mountains in the south, Kunlun-Altun-Qilian Mountains in the north (see Fig. 1), the Pamir Plateau in the west, and Hengduan Mountains in the east. It also contains the Tanggula Mountains, Gangdise Mountains, Nyainqentanglha Mountains and others on the plateau. Most of these mountains have peaks over 6000 m above sea level (a.s.l) and among them Mt. Qomolangma over 8800 m is the highest mountain peak in the world.

Geological studies showed that with the expansion of the Indian Ocean, the Indian plate continuously shifted northward and was subducted beneath the Eurasian plate, eventually causing intense

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http://dx.doi.org/10.1016/j.quascirev.2015.03.010
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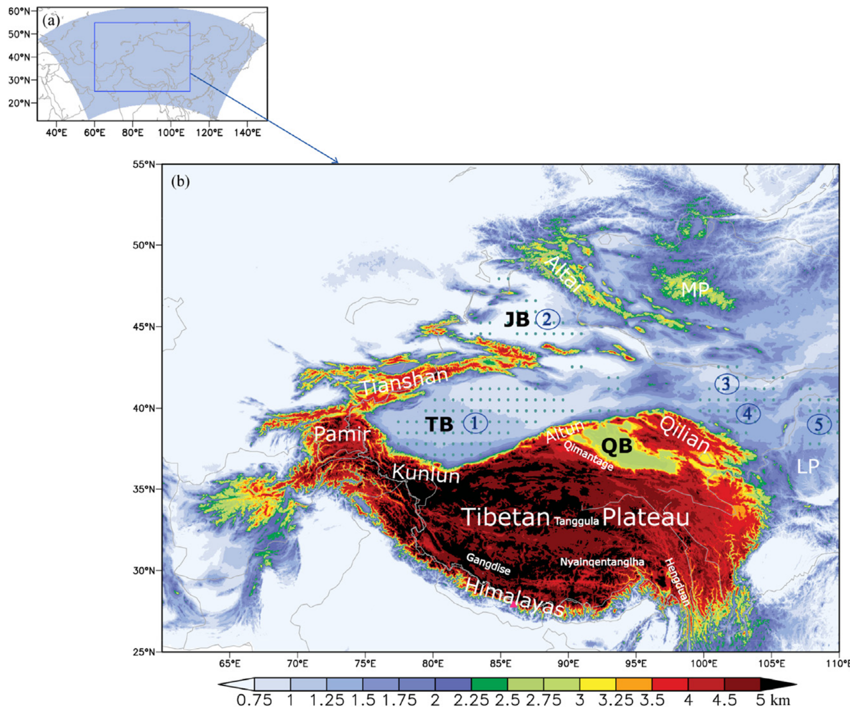

Fig. 1. Model domain (a) and distribution of major mountains and deserts surrounding the Tibetan Plateau (b). The MP and LP indicate the Mongolian Plateau and the Loess Plateau, respectively. The labels of JB, TB, and QB are for the Junggar Basin, Tarim Basin and Qaidam Basin, respectively. The numbers ①, ②, ③, ④ and ⑤ indicate the Taklimakan Desert, Gurbantunggut Desert, Badain Jaran Desert, Tengger Desert, and Mu Us Desert, respectively. The magenta triangle indicates the Mt. Qomolangma.

tectonic movements and the uplift of TP due to the strong continent-to-continent collision and continuous compression (Yin and Harrison, 2000). Though so far scientists still have different views on the timing and magnitude of the TP uplift (e.g., Molnar, 2005; Wang et al., 2014), most studies suggested that since the collision of the Indian subcontinent and the Eurasian plate at 55–45 Ma ago (Rowley, 1996; Zhu et al., 2005), tectonic movements, magmatic activities and surface uplifts all occurred in stages. Therefore, the TP underwent a phased, sub-regionally and gradually-uplifting process (Harrison et al., 1992; Chung et al., 1998; Tapponnier et al., 2001), during which episodes of erosion and planation occurred as the intermissions of uplift. For example, Tapponnier et al. (2001) proposed a multi-stage uplift model where the TP uplifted with different rates in various sub-regions, gradually advancing from south to north. Some studies suggested that large areas of the central plateau might have been uplifted to a height of 3000–4000 m in the Eocene, approximate 40–35 Ma ago (Rowley and Currie, 2006; Wang et al., 2008). In other words, the main body of the plateau might have been of certain scale much earlier. However, the northern TP and its surrounding areas, for instance, the Pamirs (Burtman, 2000; Sobel et al., 2011), the Tianshan Mountains (Sun et al., 2004; Charreau et al., 2005), the Kunlun Mountains (Zheng et al., 2000; Wang et al., 2003), the Altun mountains (Sun et al., 2005; Song et al., 2014) and the Qilian Mountains (Zheng et al., 2003; Fang et al., 2005, 2007; Zhang et al., 2014) experienced significant uplifts since the Miocene as well. Particularly the northeastern and eastern sides of the plateau constantly expanded outward, and the northeastern plateau experienced a certain level of uplift since the late Miocene or even during the Pliocene (Zheng et al., 2000; Li et al., 2014a,b). The Tianshan and Mongolian terrains also uplifted considerably in the same period (Molnar et al., 2010).

A large amount of geological evidence indicated that the northern Tibetan Plateau (NTP) and its surrounding areas had undergone notable climatic and environmental changes since the Miocene. For example, the Qaidam Basin as a whole transitioned towards aridification from the Miocene to Pliocene (Zhuang et al., 2011; Miao et al., 2013) and the Tarim Basin accumulated aeolian sands in the late Miocene to Pliocene due to extreme aridity (Zheng et al., 2000; Sun and Liu, 2006). Meanwhile, the aeolian deposition of materials from erosion in the Qilian-Kunlun-Altun Mountains of the NTP was enhanced in the Loess Plateau since the Miocene (Li et al., 2011) and the sedimentary record of the Loess Plateau also indicated the markedly intensified aridification in the Asian inland since the Pliocene (Sun and An, 2002). However, environmental changes at geological timescales rarely followed consistent trends and there had been significant fluctuations in moisture conditions of the interior Asia since the Miocene. Some local areas along the northeastern margin of the TP showed tendencies towards wetter climate during certain periods of time since the Miocene (Ma et al., 1998; Guo et al., 2002). Miao et al. (2012) systematically summarized the proxy records of environmental changes in the middle-late Miocene in Central and East Asia, finding that the large-scale aridification in Central and East Asia may be mainly controlled by global cooling, and that the spatial inhomogeneity of changes in moisture conditions in some areas of central Asia may be related to the TP uplift. This study from a macro-scale perspective pointed out the regional differences in the Asian paleoenvironmental changes and their possible causes, although this causal relation was still speculative. On a shorter timescale, fluvial and lacustrine sediments deposited during the Quaternary suggested that wetter periods occurred more recently in Chinese and Mongolian desert areas (Yang et al., 2004, 2006).

Numerical experiments using climate models have been widely applied to explorations of the causal links between the TP uplift and climate change (Liu and Dong, 2013). For example, Kutzbach et al. (1993) employed a global atmospheric circulation model and performed the “bulk-plateau uplift” experiments with no-mountain, half-mountain, and whole-mountain conditions, suggesting that the TP uplift could cause distinct variations in the Asian regional