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A Possible Impact of Cooling over the Tibetan Plateau on the Mid-Holocene East Asian Monsoon Climate

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ABSTRACT

By using a 9-level global atmospheric general circulation model developed at the Institute of Atmospheric Physics (IAP9L-AGCM) under the Chinese Academy of Sciences, the authors investigated the response of the East Asian monsoon climate to changes both in orbital forcing and the snow and glaciers over the Tibetan Plateau at the mid-Holocene, about 6000 calendar years before the present (6 kyr BP). With the Earth's orbital parameters appropriate for the mid-Holocene, the IAP9L-AGCM computed warmer and wetter conditions in boreal summer than for the present day. Under the precondition of continental snow and glacier cover existing over part of the Tibetan Plateau at the mid-Holocene, the authors examined the regional climate response to the Tibetan Plateau cooling. The simulations indicated that climate changes in South Asia and parts of central Asia as well as in East Asia are sensitive to the Tibetan Plateau cooling at the mid-Holocene, showing a significant decrease in precipitation in northern India, northern China and southern Mongolia and an increase in Southeast Asia during boreal summer. The latter seems to correspond to the weakening, southeastward shift of the Asian summer monsoon system resulting from reduced heat contrast between the Eurasian continent and the Pacific and Indian Oceans when a cooling over the Tibetan Plateau was imposed. The simulation results suggest that the snow and glacier environment over the Tibetan Plateau is an important factor for mid-Holocene climate change in the areas highly influenced by the Asian monsoon.

Key words: paleoclimate modeling, East Asian summer monsoon, mid-Holocene, Tibetan Plateau, snow and glaciers

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1. Introduction

The mid-Holocene in China is traditionally thought to be a typical interglacial period with a warmer and wetter climate in summer than the present day, and it is often called the Holocene Climatic Optimum or Megathermal period from 8.5 to 3 kyr BP with the maximum occuring in 7.2–6 kyr BP when the East Asian summer monsoon was stronger compared to today (e.g., Shi et al., 1992, 1994; An et al., 1991). The marked expansion of the Asian summer monsoon during the early to mid-Holocene was documented by paleoenvironmental records, e.g., the most notable records of vegetation changes (Winkler and Wang, 1993; Yu et al., 1998, 2000). A number of simulation studies with a global climate model have shown that insolation variation at the mid-Holocene is a primary driving force for the African and Asian summer monsoon expansion (Kutzbach and Guetter, 1986; COHMAP Members, 1988; Liu et al., 2004). However, external forcing, e.g., the Earth's orbital variations and the solar variability, can be amplified and modified through a number of feedbacks within the climate system leading to marked climate variations in the Holocene, in which the effect of the vegetation feedbacks on the climate are highly emphasized (Foley et al., 1994; TEMPO members, 1996; Claussen and Gayler, 1997; Ganopolski et al., 1998; Claussen et al.,

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1999; Wang, 1999; Brovkin et al., 2002; Diffenbaugh and Sloan, 2002). An et al. (1990, 1991) studied the evolution of the East Asian monsoon over the last 20 kyr and 130 kyr, respectively, and indicated that the variation of the monsoon climate in China is not only a response to external orbital forcing, but also related to other factors, such as the configuration of the sea and land (An et al., 1991), the uplift of the Tibetan Plateau (Ruddiman and Kutzbach, 1991), the distribution of high-latitude ice and snow, and the sea surface temperature (Porter and An, 1995). In addition, studies both from geological data and numerical modeling indicate that the Holocene optimum, as defined by peak precipitation or effective moisture, is asynchronous in the East Asian summer monsoon regions, which is related to a general weakening and southward retreat of the East Asian summer monsoon since ca. 9 kyr B.P. (An et al., 2000). Newer paleoclimate records indicate that a mid-Holocene dry interval was prevalent across the southern Mongolian Plateau along the present limits of the Asian summer monsoon (Chen et al., 2003a, b; Shi and Song, 2003). Based on the frequency of the organic radiocarbon dates collected in arid regions of China, Guo et al. (2000) showed that an extremely dry climate prevailed during 7–5.6 ^{14}C kyr BP across north central China. Huang et al. (2000) also reported that Holocene soil development in the Guanzhong basin of the central Chinese Loess Plateau was interrupted by high dust deposition at 5–6 ^{14}C kyr BP (about 5.7–6.8 kyr BP), indicating regional aridity. These new findings of the droughty climate at the mid-Holocene in northwestern China are, to a larger extent, contradictory to the traditional concept of the so-called "Megathermal" or "Climatic Optimum" which is still prevalent in the Chinese Quaternary and paleoclimate community (e.g., Shi and Kong, 1992; Shi et al., 1994). Therefore, Chen et al. (2003a) argued that, contrary to the supposedly warm and humid mid-Holocene Climatic Optimum in northwestern China, a large region of drought (lake desiccation and desertification) in central and western China along the limits of the Asian summer monsoon existed at the mid-Holocene, and as a deduction, the responsibility for the dry mid-Holocene climate in this region can probably be attributed to lower rainfall amounts due to a weaker Asian summer monsoon.

Modern climate studies show that the sensible heat flux and latent heat flux released over the Tibetan Plateau have a close relationship with the Asian summer monsoon and strongly influence the global circulation patterns (e.g., Chen et al., 1985; Yanai et al., 1992; Ye and Wu, 1998). Hence, we wonder whether the dry climate in a large region of northwestern China at about 6 kyr BP, which is supposed to be connected with the weakness of the Asian summer monsoon, is linked to the Tibetan Plateau environmental change at the mid-Holocene.

In fact, there are some reports on climate change over the Tibetan Plateau at the mid-Holocene. It is reported that glaciers advanced over the Tibetan Plateau and surrounding mountainous areas at the mid-Holocene (Lehmkuhi, 1997) and a so-called second neo-glaciation was dated to a range of 5.7–5.0 ^{14}C kyr BP, corresponding to 6.4–5.0 calendar kyr BP) (Zhou et al., 1991; Shi et al., 1994; Qin, 2002). The Guliya ice core (Thompson et al., 1997; Yao et al., 1997) on the Tibetan Plateau (located at 35°17′N, 81°29′E) is one of the most convincing records in China, spanning the Holocene to the last interglacial period. Studies on the Guliya ice core show less-negative δ^{18}O values (corresponding to the highest temperatures) in the early Holocene and more-negative δ^{18}O values after about 7 kyr BP (corresponding to rapid decreases in temperature), reaching the highest-negative δ^{18}O values (minimum temperature) during the period of 7.0–5.0 kyr BP (Thompson et al., 1997). The decrease of δ^{18}O values between the period of 7–5 kyr BP and the present is about 2‰, which equals a decrease of 3°C in surface temperature, according to the relationship of δ^{18}O values and temperature (Wang et al., 2002). Moreover, the amplitude of this temperature decrease over the Tibetan Plateau may be greater than that in other regions during the period of 7–5 kyr BP as suggested by Yao et al. (2000). Recently, Casal et al. (2004) calculated the ice-sheet mass balance for the Tibetan Plateau by using a set of data from a fully coupled ocean-atmosphere model (FOAM), showing that there was an extensive expansion of the area with positive ice-sheet mass balance from 8 kyr BP to 3 kyr BP (Casal et al., 2004, Fig. 11). This modeling result is potentially consistent with some observations, especially the observed development of the Dasuopu ice sheets (located in the southwestern region of the Tibetan Plateau) in the Holocene (Thompson et al., 2000).

Although it is still disputed whether there existed a cooling interval during the mid-Holocene over the Tibetan Plateau, it is interesting to detect the possible impact of cooling over the Tibetan Plateau on the mid-Holocene climate change. This is especially true for the East Asian monsoon climate change, as a rapid cooling of the high Asian region may have resulted in a weakened Asian summer monsoon, a response to a weakened release of the sensible heat and latent heat fluxes over the Tibetan Plateau. Because the Asian monsoon is a significant component of the global monsoon system, changes in the Asian summer monsoon may influence global atmospheric circulation patterns and climate changes in other places (Chen et al., 1985; Yanai et al., 1992; Ye and Wu, 1998).

In an attempt to explore the impacts of potential cooling over the Tibetan Plateau on Asian climate change during the mid-Holocene, with the focus on Asian summer monsoon changes at the mid-Holocene, a 9-level global atmospheric general circulation model is used to perform three numerical experiments. After describing the model and experimental design in section 2, section 3 is devoted to simulation results, with emphasis on the Asian summer monsoon domain. The study is briefly concluded in section 4.

2. Model and Experimental design

2.1 *Model*

The IAP9L-AGCM is a global grid-point atmospheric general circulation model developed by Zeng et al. (1987), Zhang (1990), and Liang (1996). The horizontal resolution is 5° in longitude by 4° in latitude, and there are nine unequally-spaced vertical levels with the top at 10 hPa. The model has been validated against present-day climate by comparing the model's results with observation-based data and with other general circulation model simulations (Bi, 1993). The model has also been used successfully for modern climate simulations of interannual climate variabilities, an atmospheric general circulation index at middle latitudes, the seasonal to interannual variability of the East Asian monsoon, and the seasonal variation of the subtropical high over the western Pacific (Wang and Bi, 1996; Wang et al., 1997). Additionally, it can reasonably describe global monsoon system in the low troposphere (Xue et al., 2001) and it holds great promise in simulating the African climate system (Chineke et al., 1997). In particular, the model has been used successfully to investigate past climate changes at the mid-Holocene (e.g., Wang, 1999; 2002), Last Glacial Maximum (e.g., Jiang et al., 2003) and middle Pliocene (Jiang et al., 2005). In the present study, the IAP9L-AGCM is employed to simulate the possible impacts of snow and glaciers over the Tibetan Plateau on East Asian monsoon climate change at the mid-Holocene.

2.2 *Experimental design*

Three numerical integrations were performed in this study. The first is the control run (CTL) in which the IAP9L-AGCM was driven by modern boundary conditions, namely solar insolation and surface conditions, including prescribed vegetation and sea surface temperature (SST), and an atmospheric CO_2 concentration of 345 ppm. The second is the mid-Holocene run (R) in which orbital parameters of 6 kyr BP (Berger, 1978) and modern surface conditions were used. The third experiment (R_ice) was the same as experiment R but with a forced condition of cooling at 6 kyr BP over the Tibetan Plateau and surrounding regions, to mimic a cooling effect of the rapid decrease in temperature at the mid-Holocene (during 7-5 kyr BP) over the Tibetan Plateau, as shown in the Guliya ice core by Thompson et al. (1997). In both experiments R and R_ice, the atmospheric CO_2 concentration was set to the same value as in the control run. To obtain the effect of cooling over the Tibetan Plateau, R_ice is designed on the basis of experiment R by replacing the modern vegetation with continental ice prescribed over the model grid cells that correspond to the area of the middle and southern parts of the Tibetan Plateau (26–34°N, 85–95°E). In this way, the modern surface vegetation prescribed in experiments CTL and R over this area, which mainly includes short grassland, meadow and shrubland as well as deciduous forest and tropical evergreen broadleaf forest, is replaced by ice cover in experiment R_ice, corresponding to a higher-albedo (increased by approximately 10%–36%) surface cover in this area, so the simulated influence of the continental ice feedback on the mid-Holocene climate can be evaluated.

3. Impacts of snow and glaciers over the Tibetan Plateau

3.1 *Temperature changes at the mid-Holocene (6 kyr BP)*

Although our simulations presented changes worldwide, we focus here on changes in the Asian domain to investigate the response of the East Asian monsoon climate to orbital forcing and to the effects of snow and glaciers over the Tibetan Plateau at 6 kyr BP. The differences between experiments R and CTL revealed pronounced responses of the IAP9L-AGCM simulation to changes in orbital parameters at the mid-Holocene. From the model-simulated boreal summer (June-July-August, JJA) surface air temperature change shown in Fig. 1a, we can clearly find a significant increase in temperature over the northern continents, especially over Eurasia and North America. The maximum increase occurring over Eurasia and North America is greater than 3.5°C, and south of 30°N, the increase is less than 3.5°C. In the Southern Hemisphere, the magnitude of temperature change is relatively smaller. When snow and glaciers are imposed over the Tibetan Plateau (Experiment R_ice), a maximum decrease in temperature exceeding 1°C and 3°C in boreal summer appears over northern Asia compared to experiment CTL (Fig. 1b) and R (Fig. 1c) respectively. The amplitude of this decrease in temperature at the mid-Holocene is comparable to that of the Guliya ice core record (Thompson et al., 1997; Yao et al., 1997) on the Tibetan Plateau (located at 35°17′N, 81°29′E). Thus, by replacing the modern vegetation with continental

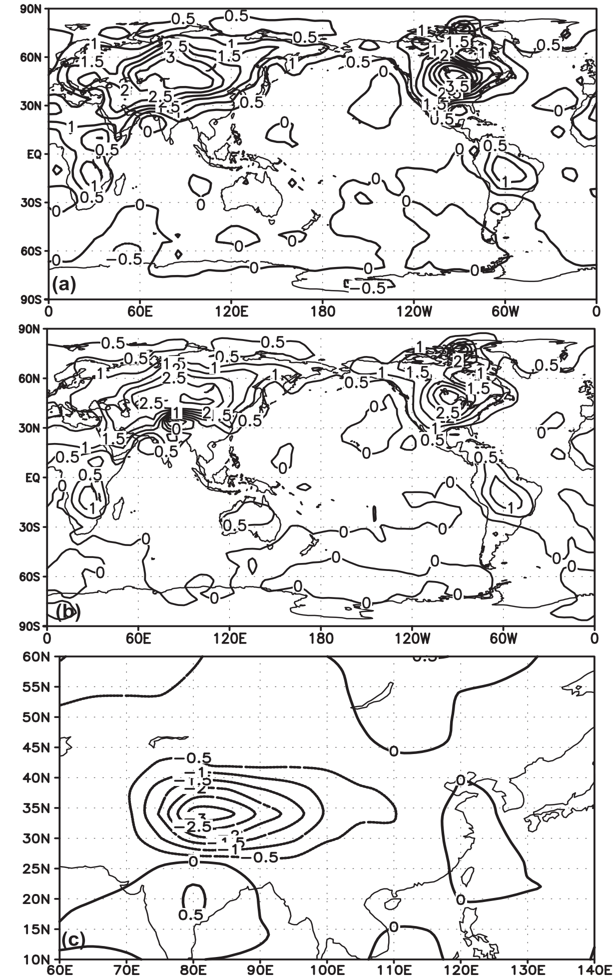

Fig. 1. Simulated changes in surface air temperatures (unit: °C) during boreal summer. (a) 6k minus 0, (b) $6k_{ice}$ minus 0, and (c) $6k_{ice}$ minus 6k (0 for present day, 6k for mid-Holocene, and $6k_{ice}$ for the mid-Holocene with ice cover over the Tibetan Plateau).

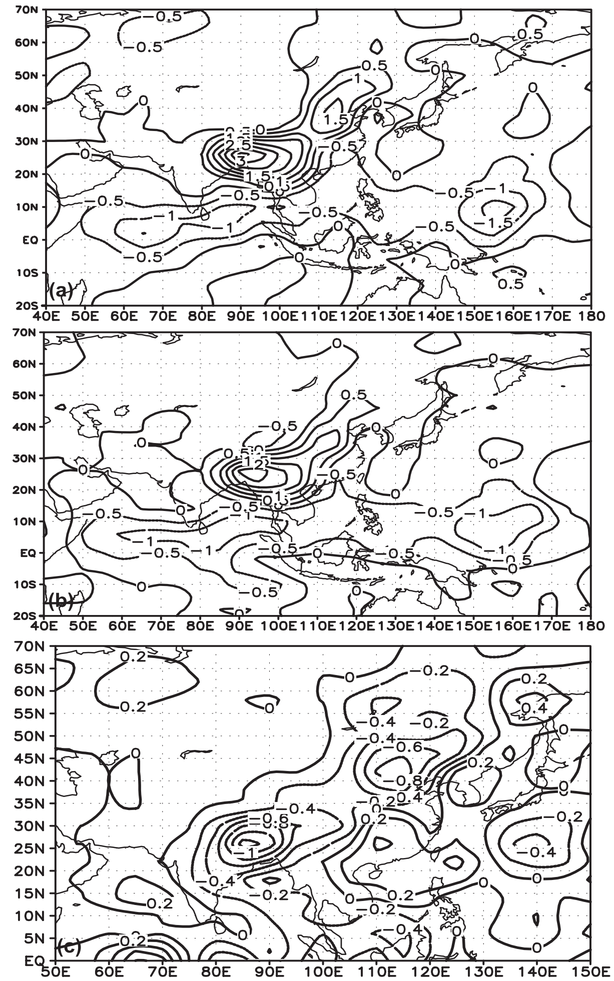

Fig. 2. Simulated changes in precipitation during boreal summer. (a) 6k minus 0, (b) $6k_{ice}$ minus 0, and (c) $6k_{ice}$ minus 6k (0 for present day, 6k for mid-Holocene, and $6k_{ice}$ for the mid-Holocene with ice cover over the Tibetan Plateau). (unit: mm d^{-1})

ice over part of the Tibetan Plateau (26°–34°N, 85°–95°E), we obtain the effect of cooling over the Tibetan Plateau in the simulation conducted with the IAP9L-AGCM.

3.2 *Precipitation changes at the mid-Holocene (6 kyr BP)*

In response to the changes of Earth orbital parameters from modern to 6 kyr BP, the simulated summer precipitation increases notably by more than 3 mm d^{-1} in the monsoon regions with a belt stretching from northern and central China southwestward through parts of South Asia. However, precipitation in Southeast Asia and in the tropical Indian and western Pacific Oceans is reduced by 0.5–1.5 mm d^{-1} on average (Fig. 2a). The geographical distribution of changes in surface air temperature (Fig. 1a) and precipitation in boreal summer can be attributed to the strengthened land-sea contrast and consequently-intensified monsoon circulation. These simulated results of temperature and precipitation changes at the mid-Holocene are almost the same as those from an earlier version of the IAP9L-AGCM, in patterns as well as in amplitudes of boreal surface air temperature and precipitation (Figures 4 and 5 in the work of Wang, 1999), and they also closely resemble the simulations of Asian monsoon climate in a coupled ocean-atmosphere general circulation model (Liu et al., 2004) and in a regional climate model (Zheng et al., 2004) as well as in an Earth system model of intermediate complexity (Jin et al., 2005).

When snow and glaciers over the Tibetan Plateau were imposed in the simulation of experiment R_ice, the spatial pattern of boreal summer precipitation

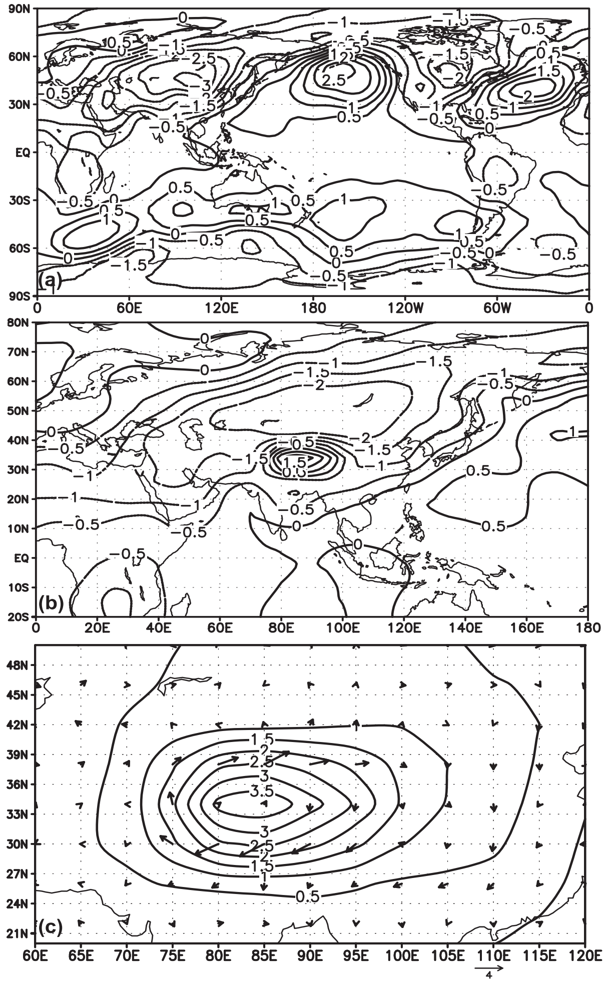

Fig. 3. Simulated changes in sea level pressure (unit: hPa) during boreal summer. (a) 6k minus 0, (b) $6k_{ice}$ minus 0, and (c) $6k_{ice}$ minus 6k (0 for present day, 6k for mid-Holocene, and $6k_{ice}$ for the mid-Holocene with ice cover over the Tibetan Plateau). In panel (c), the wind velocity (unit: m s^{-1}) at 850 hPa is overlaid on the SLP field.

changes greatly compared to experiment R, with a noticeable shrinking in spatial extent of summer monsoon precipitation over the South and East Asian continent (Fig. 2b). Furthermore, an area with reduced rainfall (over 0.5 mm d^{-1}) occurs over the northern part of the Tibetan Plateau, including part of the southern Mongolian Plateau and the Hexi Corridor, which is certain to have experienced a droughty climate at the mid-Holocene by lake geomorphologic and lithological evidence (Chen et al., 2003b). By comparison of results of the experiment R_ice with experiment R, a reduction of precipitation in boreal summer can be seen in South Asia (20°–35°N, 80°–100°E) (over 1.2 mm d^{-1}) and in parts of Central Asia (over 0.8 mm d^{-1}), including northern China along the middle and lower reaches of the Yellow River Valley and southern Mongolia. In contrast, an increase in summer monsoon precipitation (by about 0.2 mm d^{-1}) occurs over southern and eastern China, especially along the southeast coast of Eurasia (Fig. 2c). This pattern of decreased summer precipitation inland and increased summer precipitation in coastal regions may reflect the tendency of a weakened Asian summer monsoon circulation to shift the locus of summer monsoon rains southeastward as a result of the Tibetan Plateau cooling effect on the Asian summer monsoon climate change. The results of experiment R_ice can be compared to those of a similar sensitivity experiment by using an Earth system model of intermediate complexity, CLIMBER-2 (Jin et al., 2005). Although the two models have different frameworks and configurations (e.g., CLIMBER-2 has a more coarse horizontal resolution of 10° × 51° in the atmospheric module than the IAP9L-AGCM), they show quite similar temperature and precipitation distributions in the South and East Asian summer monsoon climate change during the mid-Holocene (6 kyr BP).

3.3 *Sea level pressure and atmospheric circulation changes at the mid-Holocene (6 kyr BP)*

Studies have shown that the sensible heat flux and latent heat flux released over the Tibetan Plateau drive the intense monsoon circulation and strongly influence global circulation patterns (e.g., Chen et al., 1985; Yanai et al., 1992). From the model-simulated JJA sea level pressure (SLP) change (experiment R minus experiment CTL) shown in Fig. 3a, we can clearly find a significant decrease of SLP over Northern Hemisphere continents, especially over Eurasia, and and an increase of SLP over the northern and western Pacific and Atlantic Oceans. Associated with the increased pressure gradient between the Eurasian continent and the Pacific and Indian Oceans, the South and East Asian summer monsoons are significantly reinforced (Fig. 4a) as a result of the enhanced seasonal cycle of solar insolation in the Northern Hemisphere at the mid-Holocene. A major lowering of sea-level pressure occurs over the combined region of South/East Asia and northern Africa and over southern North America (Fig. 4a). The regions of reduced SLP (compared to the control simulation) are accompanied by increased cyclonic inflow at 850 hPa (Fig. 4a). When snow and glaciers were imposed over the Tibetan Plateau, the thermally-driven summer monsoon circulation adjusted to adapt to the changes of thermal contrast between the Eurasian continent and the Pacific and Indian Oceans (Fig. 4b). Figure 4c displays the simulated distribution of the boreal summer SLP difference between the experiment R_ice and experiment CTL simulations, from which we can find an increase in SLP over the Tibetan Plateau and surrounding areas. The

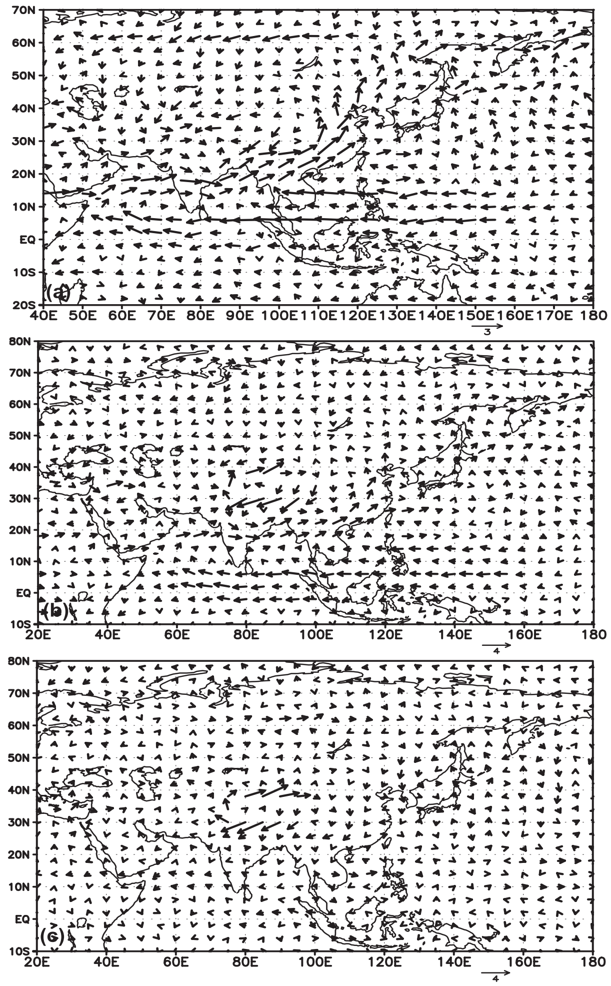

Fig. 4. Simulated changes in wind velocity at 850 hPa (unit: m s^{-1}) during boreal summer. (a) 6k minus 0, (b) $6k_{ice}$ minus 0, and (c) $6k_{ice}$ minus 6k (0 for present day, 6k for mid-Holocene, and $6k_{ice}$ for the mid-Holocene with ice cover over the Tibetan Plateau).

increased SLP accompanied by increased anticyclonic inflow at 850 hPa (Fig. 4c) over the Tibetan Plateau, weakens the low-pressure system on the Asian continent and, simultaneously, weakens the South and East Asian monsoons in boreal summer. Consequently, with the influence of the Tibetan Plateau cooling effect, the Asian summer monsoon weakened and propagated southeastward, resulting in decreased summer precipitation in South Asia, Northern China and southern Mongolia, and increased summer precipitation along the southeast coast of Asia.

4. Summary and conclusions

By using a global atmospheric circulation model, the IAP9L-AGCM, we have examined the Asian summer monsoon climate change in response to changes in orbital forcing and the feedback of a cooling effect over the Tibetan Plateau at the mid-Holocene. The simulations show that the orbital forcing, or the direct solar radiation effect, enhances the monsoon precipitation over most regions in South and East Asia at 6 kyr BP, but the feedback of the cooling effect over the Tibetan Plateau appears to weaken the Asian summer monsoon. This causes a reduction of precipitation over the South and East Asian continent but an increase in rainfall along the southeast coast of Eurasia in boreal summer, thereby counteracting the direct radiation effect, although the overall effect (direct insolation forcing plus the Tibetan Plateau cooling) results in strengthened monsoon. This tendency for the pattern of decreased precipitation inland and increased precipitation in coastal regions may reflect the tendency for the weakened Asian summer monsoon circulation to shift the locus of monsoon rains southeastward, which seems to result from a reduced heat contrast between the Eurasian continent and the Pacific and Indian Oceans when a cooling over the Tibetan Plateau appears.

Although this modeling experiment has focused on the cooling effect over the Tibetan Plateau on the mid-Holocene Asian summer monsoon change, it is also apparent that there are other factors that can amplify and/or modify the monsoonal response to orbital forcing through a number of feedbacks within the climate system leading to marked climate variations during the Holocene, such as the effects of the vegetation and oceanic feedbacks. Vegetation feedback appears to amplify the orbitally-forced enhancement of the Asian summer monsoon significantly (e.g., Wang, 1999; Zheng et al., 2004) and could play a significant role in other monsoon regions, e.g., in the enhancement of the northern African summer monsoon (e.g., Kutzback et al., 1996; Ganopolski et al., 1998; Doherty et al., 2000). Oceanic feedback can also play an important role in the mid-Holocene Asian monsoon change, but its impacts are rather inconsistent or even opposite in different model results (e.g., Hewitt and Mitchell, 1998; Liu et al., 2004; Wei and Wang, 2004). Further experiments are necessary to more precisely quantify the contribution of the cooling effect over the Tibetan Plateau versus vegetation feedbacks and oceanic feedbacks to the mid-Holocene Asian monsoon change.

Our simulations suggest that the snow and glacier environment over the Tibetan Plateau is an important factor for regional climate variability in areas highly influenced by the Asian monsoon at the mid-Holocene.

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