MM5 Simulations of the China Regional Climate During the LGM. II: Influence of Change of Land Area, Vegetation, and Large-scale Circulation Background*

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ABSTRACT

Using a regional climate model MM5 nested to an atmospheric global climate model CCM3, a series of simulations and sensitivity experiments have been performed to investigate the relative LGM climate response to changes of land-sea distribution, vegetation, and large-scale circulation background over China. Model results show that compared with the present climate, the fluctuations of sea-land distribution in eastern Asia during the LGM result in the temperature decrease in winter and increase in summer. It has significant impact on the temperature and precipitation in the east coastal region of China. The impact on precipitation in the east coastal region of China is the most significant one, with 25%–50% decrease in the total precipitation change during the LGM. On the other hand, the changes in sea-land distribution have less influence on the climate of inland and western part of China. During the LGM, significant changes in vegetation result in temperature alternating with winter increase and summer decrease, but differences in the annual mean temperature are minor. During the LGM, the global climate, i.e., the large-scale circulation background has changed significantly. These changes have significant influences on temperature and precipitation over China. They result in considerable temperature decreases in this area, and direct the primary patterns and characteristics of temperature changes. Results display that, northeastern China has the greatest temperature decrease, and the temperature decrease in the Tibetan Plateau is larger than in the eastern part of China located at the same latitude. Moreover, the change of large-scale circulation background also controls the pattern of precipitation change. Results also show that, most of the changes in precipitation over western and northeastern parts of China are the consequences of changing large-scale circulation background, of which 50%–75% of precipitation changes over northern and eastern China are the results of changes in large-scale circulation background. Over China, the LGM climate responses to different mechanisms in order of strength from strong to weak are, the large-scale circulation pattern, sea-land distribution, vegetation, CO_2 concentration, and earth orbital parameters.

Key words: sea-land distribution, vegetation, large-scale circulation background, LGM, China regional climate

1. Introduction

The LGM solar radiation is similar to that of the present day (PD). It is suggested that the primary causes for climate changes between these two periods are the distribution, extension and height of ice-sheets, sea-ice extension, SST and land-use changes; as well as the influences of CO_2 and dust. So far many studies have primarily focused on possible climate forcing mechanisms, such as the global glacial volume and land-use changes (Kutzbach et al., 1984, 1986, 1998; Tushingham and Pelitier, 1991; Masson et al., 1998; Dong and Valdes, 1998; Ganopolski et al., 1998; Kageyama et al., 1999), atmospheric CO_2 concentration variations (Manabe and Hahn, 1977; Manabe and Bryan, 1985; Weaver et al., 1998), as well as global heat transportation (Bush and Philander, 1998; Wang, 1999; Zhao et al., 2004), etc. However, these studies could not come to an agreement in general. In this study, we investigated impacts of vegetation, sea-land distribution, and large-scale circulation patterns by using a new generation of model. The impacts of earth orbital parameters, e.g., CO_2, have been discussed in Part I of the above paper (Liu et al., 2007a).

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From the model results of impacts of earth orbital parameters, e.g., CO_2, we can find that under the PD and LGM climates, changes of earth orbital parameters have minor influence on the annual mean temperature over China by a maximum of 0.12 K. However, in winter the LGM solar radiation is higher than the PD, the temperature increases by a maximum of 0.45 K. Contrasted with the winter, the LGM solar radiation is lower than the PD in summer, temperature decreases by a maximum of 0.2 K. During the LGM, CO_2 concentration reached its lowest point 2000 ppmv. This results in a temperature decrease by a little over China. The annual mean temperature decreases by 0.2 K, in winter decreases by a maximum of 0.45 K. On the contrary, CO_2 concentration has less impact in summer by 0.2 K. In some cases, temperature even increases with CO_2 concentration decreasing. This temperature increase is the outcome of decrease in cloud amount, hence increase the solar radiation that reaches the earth's surface (Liu et al., 2007a).

Our analyses are focused on regional model results, and the factors affecting regional climate are divided into two types, one is from the large-scale circulation change, and the other is from the regional change. The large-scale circulation change mainly results from ice sheet, sea ice, SST, and global land-use change, which controls the boundary conditions of regional model. The regional changes are related to regional vegetation, land-use, and sea-land distribution change. In the LGM, ice sheet reached the maximum, which took in huge seawater, made sea level drop, and altered sea-land distribution. So far, there is no study about impacts of sea-land distribution over China. The LGM climate change affects vegetation, on the contrary, vegetation change also alters climate, and both interact themselves. In the previous studies about the influences of LGM vegetation change over China, some thought that the influence is big, and others not. In this paper, we will discuss impacts of vegetation, sea-land distribution, and large-scale circulation patterns. Finally, we will synthetically discuss the roles played by earth orbital parameters, CO_2, vegetation, sea-land distribution, and large-scale circulation patterns in the LGM China climate change.

2. Sensitivity experiments

In order to obviously introduce reference and sensitivity tests, the parameters in these tests are listed in Table 1.

Table 1. Sensitivity experiments

	EOP	CO_2(ppm)	VE	SL and SST	LCB
LGM reference	LGM	200	LGM	LGM	LGM
SL test	LGM	200	LGM	PD	LGM
VE test	LGM	200	PD	PD	LGM
LCB test	LGM	200	LGM	LGM	PD

Note: EOP–earth orbit parameter; VE–vegetation; SL–sea-land distribution; LCB–large-scale circulation background.

2.1 Sea-land distribution

During the LGM, the global temperature reduced dramatically, especially over high latitudes and the land area. Two large ice sheets were formed during this period in North America and Europe. The growth of ice sheets caused a lower than PD sea-level in the extent of globe and greatly altered the sea-land configuration. At the LGM, with the exposure of East China Sea Shelf, the land area of China increased by 6.3×10^5 km^2, which was about 6.5% of the current area (Zheng et al., 2002). To study the influence of sea-land changes on the LGM climate, a sensitivity experiment was performed, in which the LGM increased land area is replaced with sea area at the PD, and the LGM land temperature replaced with the PD SST. The rest conditions are remained. Figure 1 shows land-use during the PD and LGM climates over the model domain. The data are from CLIMAP dataset <http://ingrid.ldgo.columbia.edu/SOURCES/.CLIMAP/>. With comparison of the vegetations in both periods, it is found

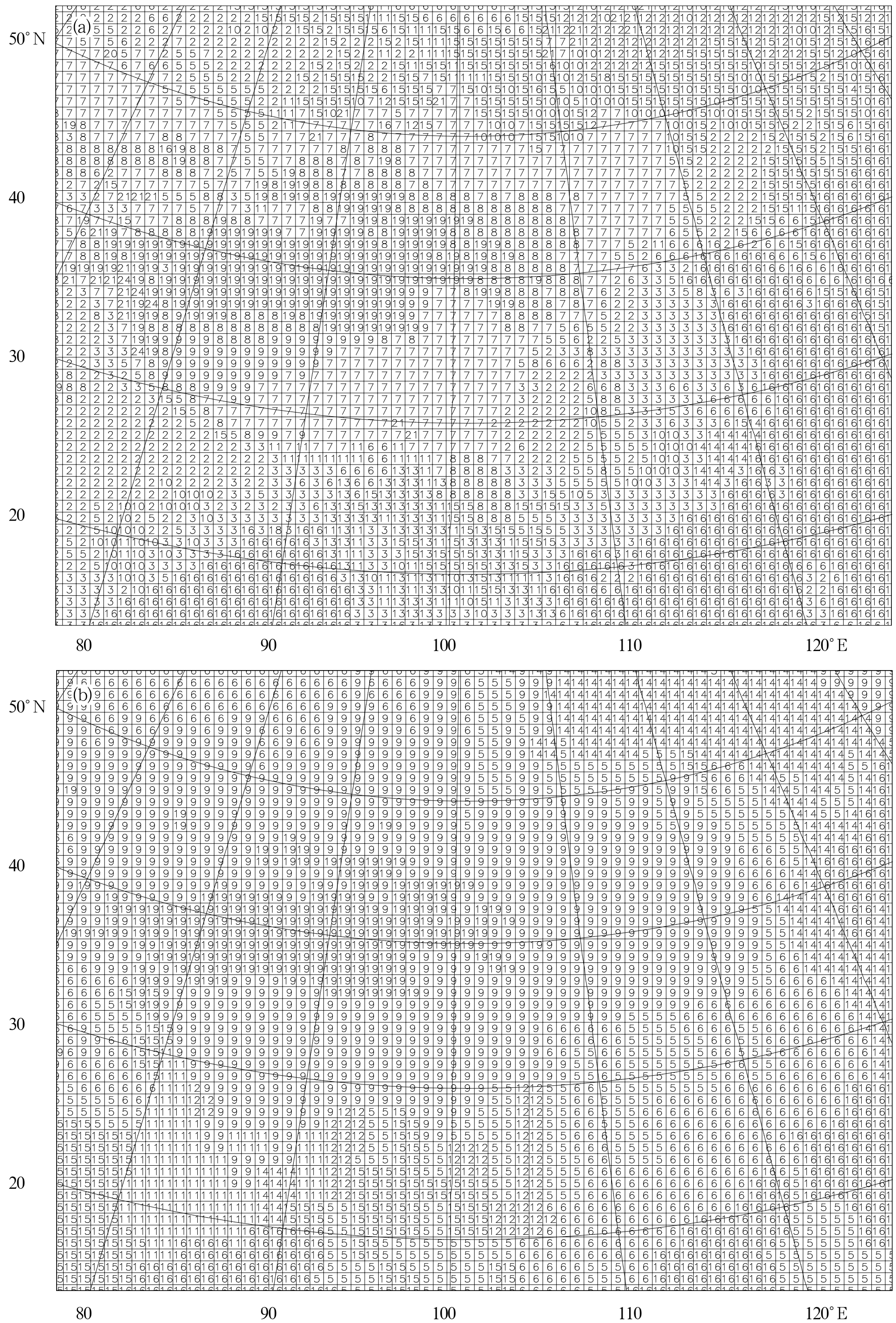

Fig.1. Land-use and vegetation of MM5 model in the PD (a) and LGM (b) scenarics. Their categories are as follows (1: Urban, 2: Dryland cropland, 3: Irrigated cropland, 4: Mixed dryland-irrigated cropland, 5: Cropland-grassland mosaic, 6: Cropland-woodland mosaic, 7: Grassland, 8: Shrubland, 9: Mixed grassland-shrubland, 10: Savanna, 11: Deciduous broadleaf forest, 12: Deciduous needleleaf, 13: Evergreen broadleaf forest, 14: Evergreen needleleaf forest, 15: Mixed forest, 16: Water bodies, 17: Herbaceous wetland, 18: Wooded wetland, 19: Barren or sparsely vegetated, 20: Herbaceous tundra, 21: Wooden tundra, 22: Mixed tundra, 23: Bare ground tundra, and 24: Snow or ice).

that the land-use changes between both periods.

Figure 2 shows the temperature differences (LGM reference run vs. SL test). Due to the changes in sea-land distribution (SL), the annual mean temperature is reduced. One of the two cooling centers is located at the Yellow Sea, with a maximum temperature decrease of 2 K; and the other is located at south of Taiwan Island, with a maximum decrease of 2.5 K (Fig.2a). Meanwhile, the temperature differences show an increase of over 0.5 K along eastern coastline, in particular, over South China, East China, and Central China. The warming center is located at South China with a temperature increase of 1.5 K. In winter, two cooling centers are formed at the Yellow Sea and Taiwan Strait with central values of −6 and −4 K, respectively (Fig.2b). These significant temperature differences are responsible for land-use changes from sea to land. As it reduces the heat capacity over this region, temperature fluctuation is increased. Hence, during winter, temperature decrease is greater over land area than over sea area, and results in the temperature decreases over these two regions. In summer, results show that the temperature increases over the Yellow Sea and Taiwan Strait and a warming center is formed over South and East China, with central values of 2 and 3 K, respectively (Fig.2c). It can be seen that the influence of sea-land distribution on LGM climate is quite localized in the coastline area over the eastern part of China.

The significant differences of temperature result in the changes of winds, and further cause changes in precipitation. Figure 3 depicts the seasonal mean differences of 850-hPa wind vectors for winter (DJF) and summer (JJA). During winter, the changes are relatively small, with stronger northeasterly winds over the Bohai Gulf and the East China Sea, and with weaker northerly winds over North and South China (Fig.3a). During summer, a cyclone is formed over the eastern part of China. As a result, it strengthened the northerly wind and weakened the summer monsoon over this area. Figure 4 shows the change of the annual mean precipitation due to the changes of

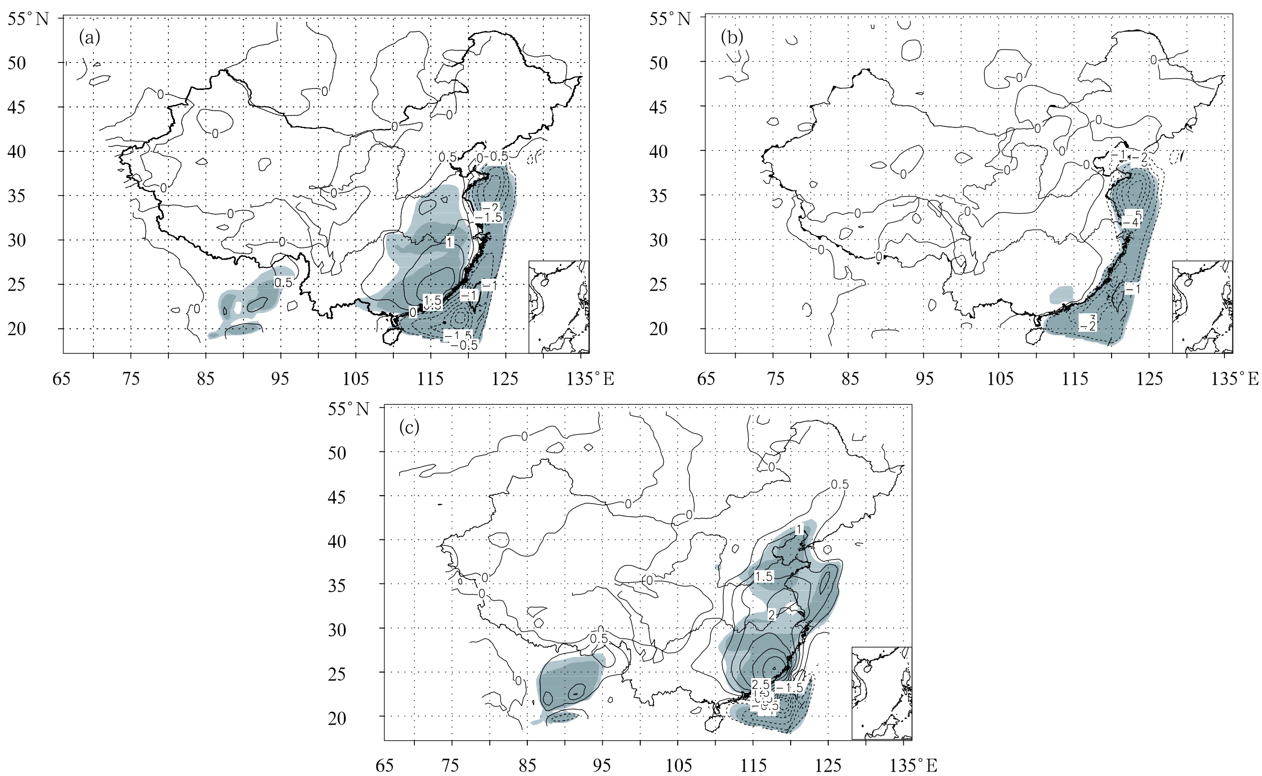

Fig.2. Temperature changes (K) resulting from changes in land-use distribution for annual mean (a), winter mean (b), and summer mean (c).

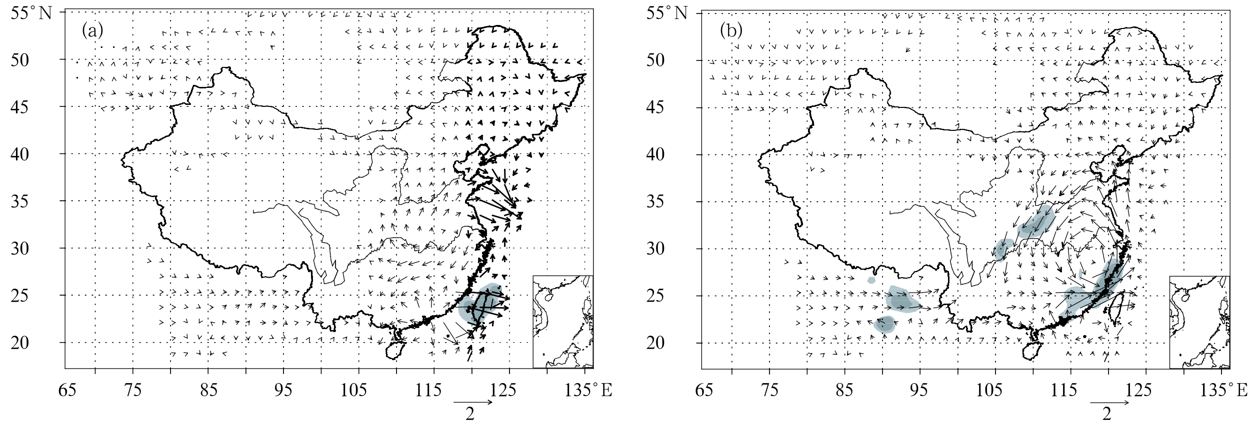

Fig.3. Changes in 850-hPa wind field (m s^{-1}) resulting from changes in land-sea distribution for January (a) and July (b).

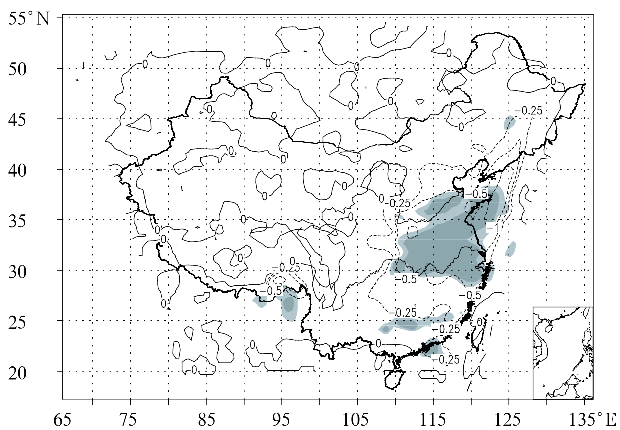

Fig.4. Changes in precipitation (mm day^{-1}) resulting from changes in land-sea distribution.

sea-land distribution. In the eastern part of China, especially in East China, precipitation reduced by 0.5 mm day^{-1}, i.e., 180 mm per year. These results are consistent with change patterns of wind. Changes in precipitation over the western part of China are not obvious.

2.2 Vegetation

During the LGM, the land-use changed significantly. In addition to the change in sea-land distribution, the vegetation distribution also transited along with climate change. Because of the cold climate, plants in temperate and frigid climate zones gradually shifted southward. In turn, changes in vegetation distribution also have influences on the LGM climate. In the previous studies, impacts of sea-land distribution and vegetation distribution on climate have not been studied separately. Instead, they were considered as one factor. Some studies concluded that the climate response to vegetation distribution is significant (Zheng et al., 2002). However, some other researches could not come up with similar results (Liu et al., 2002; Qian et al., 1998). In comparison with the previous sea-land sensitivity run (SL test as reference), another experiment (VE test) was performed to investigate the LGM climate response to the change in vegetation cover. CLIMAP vegetation data were used for this purpose.

Figure 5 shows the temperature difference due to the changes in vegetation (LGM vegetation compared with that of the PD). Results indicate that the annual mean temperature does not change significantly, with a maximum increase of 0.2 K only. Yet, winter vegetation changes result in temperature increases over the eastern part of China. The warming center is located at East China with a maximum increase of 0.7 K. No significant changes are found in the western part of China. On the contrary to the winter pattern, summer pattern shows a cooling area over the eastern part of China, with a maximum temperature decrease of 0.6 K located at Central China. Similar to the winter pattern, temperature changes during summer over western China are still quite minor. These seasonal patterns are consistent with the results of Yu et al. (2000) in the regions of mid and high latitudes of China. Results further indicate that changes in vegetation have significant impact on the eastern part of China, rather than the western part. This is mainly because that the vegetation changes over the eastern part of China are larger than over the western part, which is mostly desert areas. Although changes in the annual mean temperature are minor, the influences of vegetation on the climate over the eastern China could not be neglected. Model simulations show that the influences of vegetation change on regional winds and precipitation are not significant.

2.3 Large-scale circulation background

Regional climate change is not only influenced by radiation and changes in land-use but also controlled by the global large-scale circulation background patterns. Some studies indicated that the LGM climate is mainly affected by ice sheets and sea-ice, and to a certain degree, it is also affected by radiation and surface conditions. To the regional climate of China, the change in large-scale pattern specially means the variation of lateral boundary condition. In the previous sections we have discussed the LGM climate response to changes of radiation and land-use. This section we will discuss the influence of large-scale circulation background on the LGM China climate, by means of comparing the LGM reference run with an LCB sensitivity run, in which lateral conditions data are from the PD large-scale circulation background while keeping other parameters unchanged.

Figure 6 shows the temperature changes, revealing that the changes in large-scale circulation background lead to significant temperature differences over China. On average, temperature significantly decreased by over 7 K in Northeast China, over 3 K in the Tibetan Plateau, and about 2 K in the other areas. Comparing winter with summer patterns, in most of the model domain, winter is much cooler than summer. In winter, the greatest cooling area with a maximum temperature decrease of 14 K is located at the regions of Kazakhstan and Russia near the border of Xinjiang. In Northeast China, temperature dropped by 8 K,

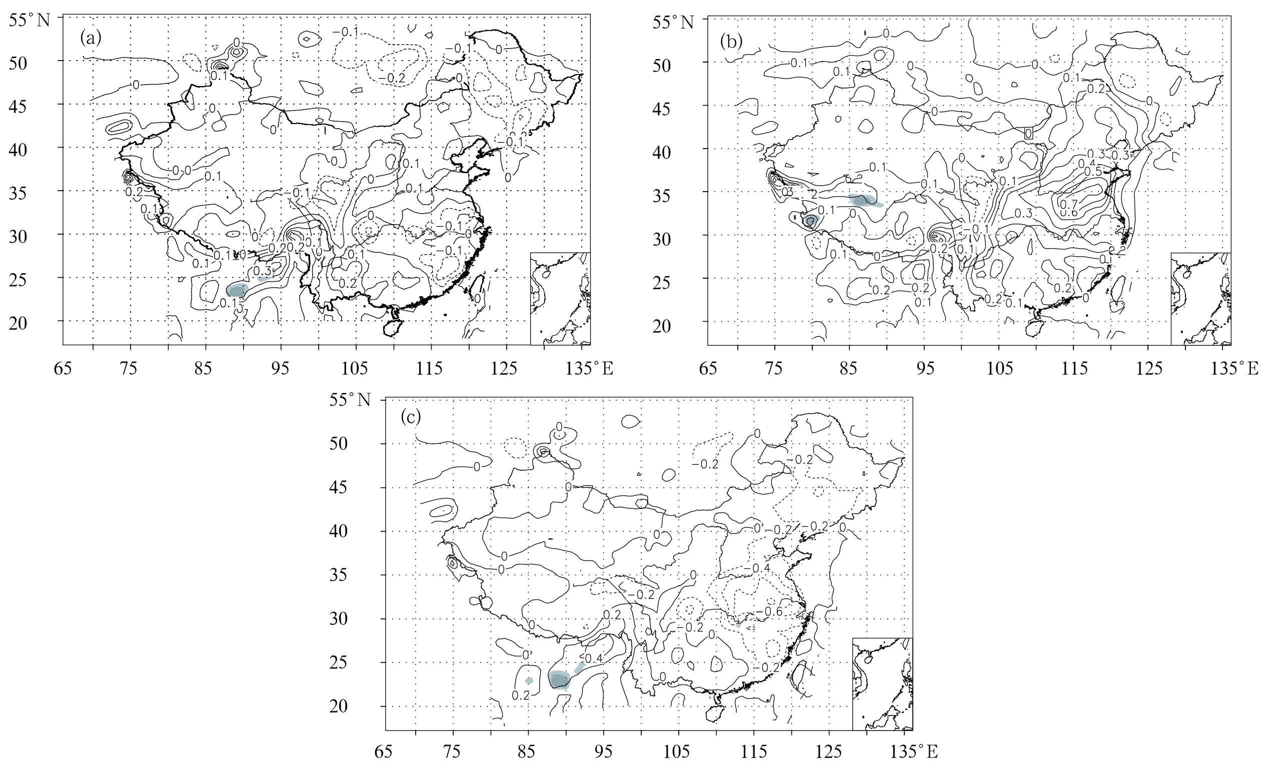

Fig.5. Temperature changes (K) resulting from changes in vegetation for annual mean (a), winter mean (b), and summer mean (c).

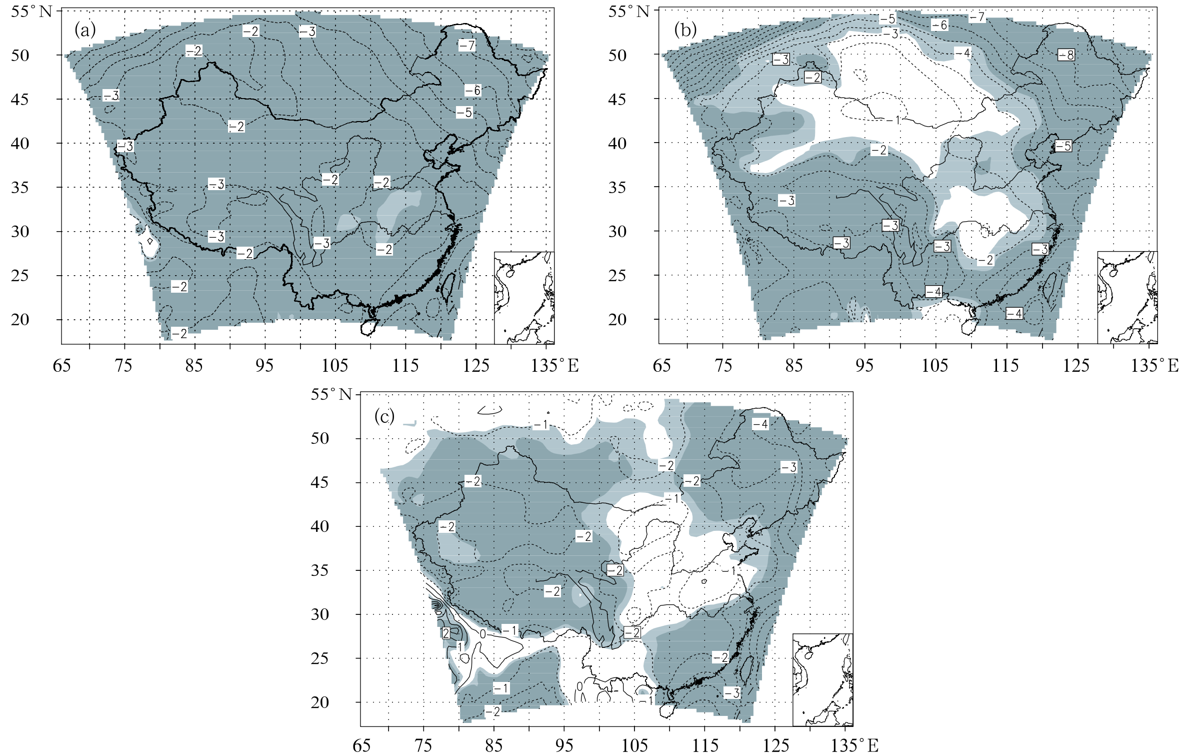

Fig.6. Temperature changes (K) resulting from changes in large-scale circulation background for annual mean (a), winter mean (b), and summer mean (c).

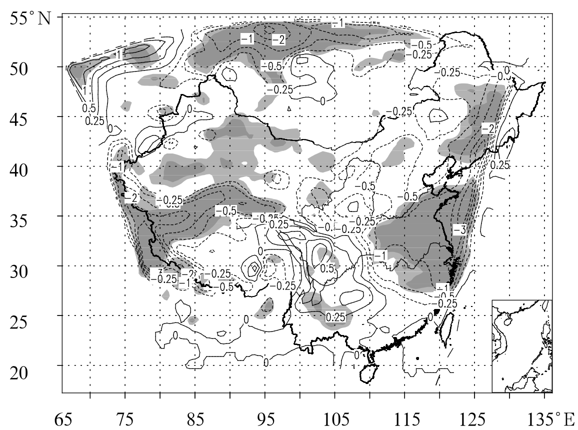

Fig.7. Changes in precipitation (mm day^{-1}) resulting from changes in large-scale circulation background.

which is the second largest one. In Mongolia and the central part of China, the least decreases in temperature are found. During summer, the decreasing magnitude is significantly weaker than in winter with a maximum decrease of 4 K. The slightest temperature changes occur over East China.

Precipitation pattern (Fig.7) shows that the LCB changes lead to precipitation decrease, and the LGM drier than the PD climate over the eastern part of China and central and western parts of the Tibetan Plateau. The maximum of precipitation decrease happens over East China by 1 mm day^{-1}, i.e., 360 mm per year. Meanwhile, the precipitation increases and the LGM climate becomes wetter than the PD climate over Southwest China, the eastern part of Tibetan Plateau, and Xinjiang. The 850-hPa wind vectors (Fig.8) indicate that, with the LCB changes, the winter winds become slightly stronger over the northern part of China and along the coasts; while weaker over Central China, Southwest China, and South China. Over south of North China, summer monsoon becomes significantly weaker in the LGM than in the PD. This resulted in decreases in precipitation in this area.

3. Conclusions

From the above analyses, it can be seen that changes of sea-land distribution during the LGM

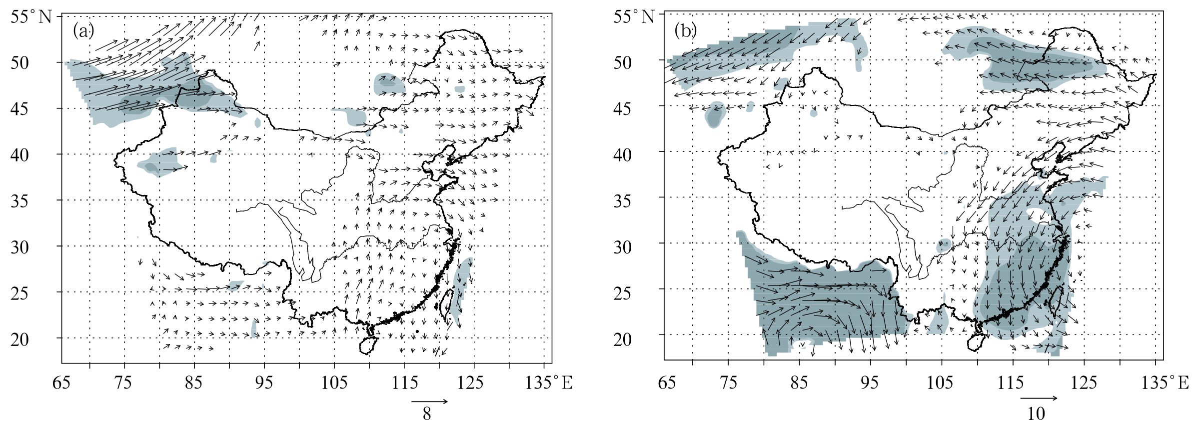

Fig.8. Changes in 850-hPa wind field (m s^{-1}) resulting from changes in large-scale circulation background for January (a) and July (b).

result in temperature decreases in winter and increases in summer. It has significant impacts on temperature and precipitation in particular, over the east coastal region of China. As a result, in the total precipitation change, about 25%–50% of the change is from changes of sea-land distribution over the region. On the other hand, the changes in sea-land distribution have less influence on the climate of inland and western part of China. During the LGM, significant changes in vegetation distribution occurred over the eastern part of China. Plants in moderate and frigid climate zones gradually shifted southward. Vegetation in the tropics shrank. This results in temperature alternating with winter increase and summer decrease. The LCB change has significant influence on temperature, precipitation, and monsoon over China. It results in temperature decrease, and directs the major pattern of temperature variations and its characteristics. For example, Northeast China has the greatest temperature decrease, and the temperature decrease in the Tibetan Plateau is larger than in eastern China at the same latitude. Meanwhile, the LCB changes also control the precipitation pattern. Results show that most of the changes in precipitation in west and northeast parts of China are the consequences of large-scale background variations, of which 50%–75% of precipitation changes over North and East China are the results of LCB changes.

The series of sensitivity experiments performed in this study enabled us to further understand the LGM regional climate of China. Results indicate that the variations of air temperature, winds, and precipitation are primarily caused by LCB changes; then influenced by land-use changes. Among the latter, the sea-land distribution has significant impact on the temperature and precipitation over the eastern part of China. During the LGM, significant changes in vegetation distribution result in temperature alternating with winter increase and summer decrease. In comparison with the PD climate, the effect of earth orbital parameter change at LGM has not changed too much. Its influences on the LGM climate over China are then relatively minor. However, the influence on seasonal mean temperature changes in magnitude, with a maximum of 0.4 K rising in winter and 0.3 K falling in summer. Therefore, the influence of orbital forcing cannot be neglected. In the LGM, CO_2 concentration reached its lowest point 200 ppmv. The reduced CO_2 leads to temperature decrease, and its magnitude is somewhat higher than that caused by orbital parameter changes. In conclusion, over China, the relative LGM climate responses to different mechanisms in order of strength from strong to weak are, the large-scale circulation background, sea-land distribution, vegetation, CO_2 concentration, and earth orbital parameters.

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