MM5 Simulations of the China Regional Climate During the Mid-Holocene*

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(Received May 6, 2009)

ABSTRACT

Using a regional climate model MM5 nested with an atmospheric global climate model CCM3, a series of simulations and sensitivity experiments have been performed to investigate responses of the mid-Holocene climate to different factors over China. Model simulations of the mid-Holocene climate change, especially the precipitation change, are in good agreement with the geologic records. Model results show that relative to the present day (PD) climate, the temperature over China increased in the mid-Holocene, and the increase in summer is more than that in winter. The summer monsoon strengthened over the eastern China north of 30°N, and the winter monsoon weakened over the whole eastern China; the precipitation increased over the west part of China, North China, and Northeast China, and decreased over the south part of China. The sensitive experiments indicate that changes in the global climate (large-scale circulation background), vegetation, earth orbital parameter, and CO₂ concentration led to the mid-Holocene climate change relative to the PD climate, and changes in precipitation, temperature and wind fields were mainly affected by change of the large-scale circulation background, especially with its effect on precipitation exceeding 50%. Changes in vegetation resulted in increasing of temperature in both winter and summer over China, especially over eastern China; furthermore, its effect on precipitation in North China accounts for 25% of the total change. Change in the orbital parameter produced the larger seasonal variation of solar radiation in the mid-Holocene than the PD, which resulted in declining of temperature in winter and increasing in summer; and also had an important effect on precipitation with an effect equivalent to vegetation in Northeast China and North China. During the mid-Holocene, CO₂ content was only 280×10⁻⁶, which reduced temperature in a very small magnitude. Therefore, factors affecting the mid-Holocene climate change over China from strong to weak are large-scale circulation pattern, vegetation, earth orbital parameter, and CO₂ concentration.

Key words: mid-Holocene, China, earth orbital parameter, vegetation, large-scale circulation background


1. Introduction

The mid-Holocene (6 ka B.P.) is the last period of the warmest climate with roughly 6000 yr before the present day (PD). A great deal of geological records indicate that the mean annual temperature in the mid-Holocene over eastern China is 2.5 K higher than that in the PD, while the temperature over western China is about 3–4 K higher than that in the PD (An et al., 1990; Shi et al., 1992; Zhang, 1993; Yu et al., 2001). Pollen and vegetation records in China show that in mid-Holocene the vegetation in China moved northward, which implies that the temperature then is higher than that in the PD (Yu et al., 1998a, b; Yu and Wang, 2000). In general, summer monsoon in China is stronger in the mid-Holocene than that in the PD, and the climate is getting warmer and wetter. As warm climate in the mid-Holocene is similar to the climate due to CO₂ increase, the researches on the climate in the mid-Holocene become important, which have been a reference to global and future climate change.

In the Palaeoclimate Modeling Intercomparison of the 1990s, 18 climate models have been selected to...
simulate the climate in the mid-Holocene under uniform conditions (Joussaume et al., 1999), such as CCM2 (Kutzbach et al., 1998), UGAM2.0 (Hall and Valdes, 1997), etc. The results from these models show that temperature enhances in the mid-Holocene over Eurasian continent in summer while declines in winter. However, the geological records illustrate that the climate in winter is warmer in the mid-Holocene than in the PD over China. This is different from the model results due to solar radiation forcing, which implies that there are some shortages in the model results. Moreover, the model results show that precipitation increases in the mid-Holocene over East Asia, and precipitation increases occur in western China and India (25°–35°N, 80°–95°E). The magnitude of precipitation increase from each model is not agreeable. The distributions of modeled precipitation increases are not in complete accord with the geological records.

Solar radiation in the mid-Holocene is 5% stronger in summer, but 5% weaker in winter than that in the PD. Some explanations of the temperature increase in winter over China and North America are given. The results indicate that climate changes in the mid-Holocene correlate closely with vegetation changes (Crowley and Baum, 1997; Wang, 1999; Claussen et al., 1999). Feedback from the vegetation results in the temperature enhancement in winter over China. Then some works further demonstrate the vegetation role (Chen et al., 2002; Wang, 2002; Zheng et al., 2004). Previous studies mainly focus on the impacts of vegetation and earth orbit on the climate of China during the mid-Holocene. In this study, we investigate the impacts of all these factors including earth orbital parameters, CO2, vegetation, and large-scale patterns on climate change using a new generation model. In addition, recent researches have shown that droughts occurred in Shanxi and Inner Mongolia in the mid-Holocene. Based on that the viewpoint about the East Asian monsoon decline in the mid-Holocene was proposed by Chen et al. (2004). We will discuss this phenomenon as well.

2. Model description

With the rapid development of computer and parallel technology, mesoscale meteorological models have been developed from a hydrostatic model–MM4, to the new generation–MM5 using non-hydrostatic, primitive equation. With the development of models, weather forecast models and climate models are gradually unified in many aspects. For example, in order to enhance forecast efficiency, previous forecast models have simplified radiation and land surface schemes, which are two essential processes in the climate modeling. Now, they have been included in the new generation models such as MM5 and RAMS. Thus, these models can also be used in climate simulations and studies. MM5 has been widely used for these purposes (Tang et al., 2004). It is a non-hydrostatic model with Plein-Xiu land surface scheme. Based on the MM5 version 3, we adopt the Graupel moisture scheme, Grell cumulus parameterization scheme, Plein-Xiu PBL coupled with Plein-Xiu land surface scheme, and RRTM radiation scheme. It has a 90-km horizontal resolution with 23 vertical levels. The model domain covers the entire China.

Previous studies primarily used global climate models (GCMs) in paleoclimatic research. These models have relatively low resolution, which could not accurately represent the regional changes. In particular, the climate models may not capture the regional climate response to vegetation change. In this study, we use a regional climate model MM5 nested to an atmospheric global climate model CCM3 in order to enhance the model resolution in the China region, and to offset the low resolution of the GCM. In addition, the CCM3 and MM5 used in this study are advanced in comparison with the CCM1 and RegCM2 (equivalent to MM4 climate model), which have been used in previous studies (e.g., Zheng et al., 2004). The CCM3 and MM5 have been used in the simulations of the Last Glacial Maximum (LGM) climate over China (Liu et al., 2008a, b).

3. The climate in the mid-Holocene

Based on the geological records, main characteristics of the climate in the mid-Holocene and the differences between the mid-Holocene and PD climate are known. By comparing geological records with simulated temperature differences as well as changes of precipitation and winds between the climates of PD and
mid-Holocene, it is possible to evaluate the model ability in simulating the mid-Holocene climate. When the regional model (MM5) is used to simulate the climate over China, the CCM3 provides boundary conditions. The parameters such as the earth orbital parameters, vegetation over China (Yu et al., 1998b), distributions of sea-land, topography and sea-surface temperature (Wang, 1999; Chen et al., 2002), and lower boundary conditions of CCM3 are listed in Table 1, in which the vegetation is as in the PD except over China. The CCM3 runs for 25 yr, and the results of the last 10 years are analyzed.

<table>
<thead>
<tr>
<th>Parameters and conditions of PD and 6-Ka B. P. climate</th>
<th>Earth orbital parameters</th>
<th>CO₂ (µL L⁻¹)</th>
<th>VE</th>
<th>SST, TO and SL</th>
</tr>
</thead>
<tbody>
<tr>
<td>PD</td>
<td>0.016724</td>
<td>23.446</td>
<td>282.039</td>
<td>345 PD</td>
</tr>
<tr>
<td>6-Ka B. P.</td>
<td>0.018682</td>
<td>24.105</td>
<td>180.87</td>
<td>280 6-Ka B. P.</td>
</tr>
</tbody>
</table>

Note: ECC: eccentricity; DEC: declination; PRE: precession; TO: topography, VE: vegetation, and SL: sea-land distribution.

Figure 1 depicts CCM3 simulated differences of surface air temperature between the PD and mid-Holocene climates (the shades indicate a confidence level of 95% from the t-test). The results show that mean annual surface air temperature decreases over northern North Europe, Greenland, and north of 80°N while increases over other areas of the globe, with a maximum of 2 K occurring in Novosibirsk, Irkutsk, and Northeast China. In summer, temperature enhances over global land areas. The 2-K maximum temperature increase occurs over high latitudes of Asia, Australia, and Antarctic. In winter, there is a zone around 60°N where temperature increases over Europe, Asia, and America. The temperature increase over high latitude of Asia reaches 5 K. The temperature decreases over most of the global land areas and the temperature decrease over Arctic is the biggest. The temperature over most of East Asia changes a little, with the maximum temperature decrease of 1 K.

Figure 2 shows CCM3 simulated wind changes between the PD and mid-Holocene climates. From Fig. 2a, it is found that in summer there are two anticyclones over Pacific and Atlantic Ocean, respectively. Namely, subtropical highs over the Northern Hemisphere enhance in the mid-Holocene. Over eastern part of China, south-easterly and southerly winds enhance, which indicates that the East Asian summer monsoon becomes stronger. Figure 2b delineates that in winter westerly winds in high latitudes of the Northern Hemisphere enhance, so do the southwesterly winds over middle Asia, Xinjiang and Mongolia.

The southwesterly wind changes accord with temperature increases over Novosibirsk and its surroundings. Similar situations appear in eastern Pacific Ocean and North America. There are two anticyclones over Pacific Ocean, Atlantic Ocean, and North Europe, which illustrates that the Aleutian low and Iceland low become weaker. The winter monsoon over eastern China also declines. CCM3 modeled changes of mean annual precipitation between the PD and mid-Holocene are shown in Fig. 3. The mean annual precipitation increases over most of China except Shaanxi and Shanxi. CCM3 results are generally agreeable with previous works (Joussaume et al., 1999; Wang, 2002), such as mean annual temperature increase, temperature increase in summer, temperature decrease in winter, summer monsoon enhancing over East Asia, winter monsoon declining and precipitation increase over East Asia. This indicates that CCM3 model is able to simulate impacts of earth orbit change on the climate.

Based on CCM3 model results, some experiments are performed with regional model MM5. The parameters and boundary conditions used in MM5 are also listed in Table 1. Refer to Liu et al. (2008a) for MM5 modeled results about the PD climate. Figure 4 presents MM5 modeled climate changes between the PD and mid-Holocene, including surface air temperature, precipitation, and wind changes. From Fig. 4a, it is found that MM5 modeled mean annual surface air temperatures increase by 0.3–2.1 K. The temperature enhances by 2 K between the Yellow River and the middle and low reaches of the Yangtze River while the temperature increases by 1.5 K over North-
east China. The minimum temperature increase occurs in the Hetao Area with only 0.3 K. The temperature increases over the eastern and northern Tibetan Plateau are 1.2 K, and 0.3–0.6 K over the southern

Fig. 1. CCM3 modeled temperature differences between the mid-Holocene and the PD for (a) annual mean, (b) summer, and (c) winter. The shadings indicate a confidence level of 95% from the t-test.
Fig. 2. CCM3 modeled differences in 850-hPa wind vector between the mid-Holocene and the PD for (a) summer and (b) winter. The shadings indicate a confidence level of 95% from the t-test.

Fig. 3. As in Fig. 2, but for annual mean precipitation.
Fig. 4. The differences in temperature (K), precipitation (mm day$^{-1}$) and 850-hPa wind field between the mid-Holocene and the PD for (a) mean annual temperature, (b) winter (DJF) temperature, (c) summer (JJA) temperature, (d) mean annual precipitation, (e) wind in January, and (f) wind in July. Dark and light shadings indicate a confidence level of 95% and 90%, respectively, from the $t$-test.

part of the Tibetan Plateau. MM5 modeled temperature changes over eastern China are in accordance with the geological records while MM5 modeled temperature changes over western and northern parts of China are lower than the geological records (An et al., 1990; Shi et al., 1992; Zhang, 1993; Yu et al., 2001). In winter, the temperatures enhance over most of China except the southern part of the Tibetan Plateau and Yunnan. The temperature increases become bigger with the increase of latitudes over northern China. There is a high center of temperature increases over the middle and low reaches of the Yangtze River with a maximum of more than 1 K. In summer, there is a high center over Hubei, Henan, and Anhui with a maximum of 4.5 K. There is a high center over northwestern Tibetan Plateau with a maximum of 2 K. These results are similar to that of Zheng et al. (2004).

MM5 modeled precipitation changes (Fig. 4d) show that the precipitation increases over western and northern China, while decreases over southern China. A high center of the precipitation increase appears in central and eastern Inner Mongolia with a max-
imum of 1 mm day\(^{-1}\). The precipitation increases north of 35\(^\circ\)N over eastern China. The lake records indicate that lake levels over western China, North China, and Northeast China, are higher in the mid-Holocene than that in the PD, which means that the precipitation over these regions may be higher. But the lake levels over south are lower in the mid-Holocene than that in the PD (Yu et al., 2001; Qin et al., 1997). Therefore, MM5 modeled precipitation changes agree with the lake records reasonably. Some recent researches demonstrate that the lake level over Alashan declines in the mid-Holocene, and the drought happens, which is associated with the precipitation change and drought on the Qilian Mountain (Chen et al., 2004). Meanwhile, the droughts occur over Guanzhong and surroundings of the Tibetan Plateau (Chen et al., 2004). The model results indicate that the precipitation decreases over Guanzhong and surroundings of eastern and southern Tibetan Plateau, which matches with geological records. But MM5 model does not reproduce precipitation decrease over the Qilian Mountain. This will be discussed in last section of this paper.

MM5 modeled wind changes (Figs. 4e, f) illustrate that the winter monsoon over eastern China becomes weaker. In summer, wind over southern China alters a little. Wind in north of 30\(^\circ\)N over eastern China strengthens, namely, southeasterly and southerly winds from Pacific Ocean enhance. The t-test is performed for the model results. Dark and light shades indicate a confidence level of 95% and 90%, respectively, from the t-test. The above model results and comparisons suggest that the model is able to reproduce main features of the mid-Holocene climate over China, in which the modeled precipitation changes are agreeable with geological records decently.

It is well known that climate change between the PD and mid-Holocene is the synthetic effect of many factors. The climate change in the mid-Holocene provides a real example for investigating the roles of climate factors such as CO\(_2\), vegetation, and earth orbit in climate change. In order to explore regional climate change over China, four factors including earth orbit parameters, CO\(_2\), vegetation, and large-scale circulation background change (LCB) are examined. The LCB affects climate through boundary conditions of the regional model. The parameters and boundary conditions of these sensitive tests are listed in Table 2.

<table>
<thead>
<tr>
<th>Sensitive experiments</th>
<th>EOP</th>
<th>CO(_2) ((\mu L) L(^{-1}))</th>
<th>VE</th>
<th>SL, SST</th>
<th>LCB</th>
</tr>
</thead>
<tbody>
<tr>
<td>PD reference</td>
<td>PD</td>
<td>345</td>
<td>PD</td>
<td>PD</td>
<td>PD</td>
</tr>
<tr>
<td>6-kaBP reference</td>
<td>6 kaBP</td>
<td>280</td>
<td>6 kaBP</td>
<td>PD</td>
<td>6 kaBP</td>
</tr>
<tr>
<td>EOP test</td>
<td>PD</td>
<td>280</td>
<td>6 kaBP</td>
<td>PD</td>
<td>6 kaBP</td>
</tr>
<tr>
<td>CO(_2) test</td>
<td>6 kaBP</td>
<td>345</td>
<td>6 kaBP</td>
<td>PD</td>
<td>6 kaBP</td>
</tr>
<tr>
<td>VE test</td>
<td>6 kaBP</td>
<td>280</td>
<td>PD</td>
<td>PD</td>
<td>6 kaBP</td>
</tr>
<tr>
<td>LCB test</td>
<td>6 kaBP</td>
<td>280</td>
<td>6 kaBP</td>
<td>PD</td>
<td>PD</td>
</tr>
</tbody>
</table>

Note: EOP: earth orbit parameter; VE: vegetation; SL: sea-land distribution; LCB: large-scale circulation background. The SL, VE, and LCB tests are depicted in another paper.

4. Sensitivity experiments

4.1 Earth orbital parameters

The earth-atmosphere system absorbs energy from the sun. Thus, the variations of earth orbital parameters are important to the global climate system. To understand their impact on the mid-Holocene climate over China, we used the PD earth orbital parameter in the mid-Holocene sensitivity run, while fixed the rest conditions. Figure 5 portrays differences of surface air temperature between the reference and sensitive runs. The changes of mean annual temperature (Fig. 5a) delineate that the earth orbit variation results in temperature decreases over most of China during the mid-Holocene, which ranges from -0.3 to 0.1 K. The temperature changes are relatively small, and the changes over eastern China are a little higher than that over western China with 0.3-K maximum temperature decrease in Northeast and South China. This result is different from previous conclusions because the reference climates are different. The reference climates in previous works refer to the PD climate, but in our
Fig. 5. The temperature differences (K) resulted from the change of earth orbit between the mid-Holocene and the PD for (a) annual mean, (b) winter (DJF), and (c) summer (JJA).

work, it refers to the mid-Holocene climate. Since vegetations in the two climates are different, their response to solar radiation change are also different.

Although the changes of the mean annual temperature are small, temperature changes in each season are not the same. This is because solar radiation changes in each season are different. In winter, the temperature reduces mostly over China (Fig. 5b). The temperature decreases over eastern China are bigger than that over western China, especially it drops by an maximum of 0.9–1.0 K over South China and east Inner Mongolia, while it changes a little over the Tibetan Plateau. In summer, temperature enhances over most parts of China. The temperature increases over western China are relatively bigger than other areas with a maximum of 0.6 K. The temperature changes in spring and fall are between that in winter and summer.

The above temperature changes correspond to solar radiation variations. Meanwhile, precipitation and wind also change over China. Figure 6 shows that the earth orbit variation brings about the precipitation increases over China during the mid-Holocene. The increases over North China and Northeast China are most significant with a maximum of 0.25 mm day$^{-1}$. Figure 7 depicts wind changes due to the earth orbit variation. In winter, the temperature drops due to solar radiation decreases make the winter monsoon in East China stronger. In summer, the temperature increases due to solar radiation strengthening make the southwest monsoon and East Asian monsoon in

Fig. 6. The precipitation difference (mm day$^{-1}$) resulted from the change of earth orbit between the mid-Holocene and the PD.
eastern part of China stronger. This is in accordance with the precipitation changes.

4.2 CO$_2$

The global climate is not only driven by the solar radiation, but also influenced by the energy distribution in the climate system. The variation of atmospheric CO$_2$ concentration is an important factor that influences the energy distribution and balance in the climate system. Keeping other conditions of the mid-Holocene reference unchanged (Table 2), we used CO$_2$ concentration in the PD (345 ppmv) to run the sensitivity experiment in order to understand the mid-Holocene climate response to the CO$_2$ concentration change. Figure 8 shows the temperature differences between two model simulations (reference-CO$_2$ test). The annual mean temperature differences shown in Fig. 8a indicate a much cooler area located in eastern part of Inner Mongolia with the maximum of $-0.15$ K. Over South China, the difference is $-0.10$ K. Fewer changes are found over western China. Because the boundary conditions have not changed, the differences tended to be gradually smaller when approaching the boundary. This relatively slight effect would not have significant impact on precipitation and wind components. Figures 8b and 8c present the temperature differences driven by CO$_2$ forcing for winter and summer, respectively. Among four seasons, the impact of CO$_2$ concentration in winter is the most significant, with a maximum temperature decrease of 0.2 K. The temperature over eastern China drops by 0.1 K. During summer, the impact of variation of CO$_2$ concentration is very limited. In some regions such as Inner Mongolia, Northeast China, and the Tibetan Plateau, temperature even increases. This results from cloud changes, which bring about changes of radiative flux. The temperature responses to the variation of CO$_2$ concentration in spring and autumn are between that in winter and summer.

4.3 Vegetation

During the mid-Holocene, the vegetation distribution also transits along with the climate change. Because of the warm climate, plants in tropic and temperate climate zones gradually shifted northward, and plants in frigid climate zones reduce gradually. In turn, the changes in vegetation distribution also have influences on the mid-Holocene climate. In previous studies, changes of vegetation distribution result in the increases of mean annual temperature and temperature in winter. However, there are contradicting results with respect to impacts of vegetation distribution changes on climate in summer, namely, (1) the vegetation distribution changes result in temperature decreases (Zheng et al., 2004), and (2) they bring about temperature increases (Chen et al., 2002). The vegetation distributions in the mid-Holocene are based on geological records, such as pollen etc. (Yu et al., 1998b). Figure 9 indicates the vegetation distributions in the PD and mid-Holocene.

Figure 10 delineates the temperature difference due to the changes in vegetation (reference vs. vegetation test). Results indicate that the mean annual temperature change significantly over east part of China,
Fig. 8. Temperature differences (K) resulted from change of CO₂ content between the mid-Holocene and the PD for (a) annual mean, (b) winter (DJF), and (c) summer (JJA). With a maximum increase of 0.8 K. In winter, the vegetation changes result in the temperature increase over eastern China. The warming center is located in South China with a maximum increase of 1.2 K. But no significant changes are found in western China. In summer, the vegetation changes bring about temperature rises over eastern China, with a maximum temperature increase of 1.1 K. Moreover, the temperature also enhances obviously during summer over West China, such as eastern Tibetan Plateau. These seasonal patterns are consistent with the results of Chen et al. (2002). From vegetation data (Yu et al., 1998b), it is found that the vegetation changes are bigger over eastern China than over western China in the mid-Holocene.

Because the vegetation changes in the mid-Holocene result in the temperature changes, precipitation and wind also change correspondingly. Figure 11 indicates that the vegetation changes bring about the precipitation increases over China. The significant increases occur in North China, southern part of the Tibetan Plateau, and Sichuan basin with a maximum increases of 0.25 mm day⁻¹. The wind changes at 850 hPa are depicted in Fig. 12. In winter, an anticyclone appears in South China because of the temperature increases over eastern China, which induces winter monsoon in most of eastern China to become weaker and wind along coast to strengthen. In summer, a cyclone happens in Hubei and Henan due to the temperature enhancing, which brings about strong summer monsoon over eastern China. Compared with wind changes in the mid-Holocene, the wind changes due to the vegetation changes are limited.

4.4 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 patterns. For the regional climate of China, the change in large-scale circulation background means the changes of lateral boundary conditions. In previous sections, we have discussed the mid-Holocene climate response to
changes of radiation and land-use. In this section, we will discuss the influence of large-scale circulation background on the mid-Holocene climate. By means of comparing the reference run with an LCB sensitivity run, in which the lateral condition data are from the PD large-scale circulation while other parameters are kept unchanged. Figure 13 shows the temperature changes, which reveals that the changes in large-scale circulation background lead to significant temperature differences over China. During the mid-Holocene, the mean annual temperature significantly increased with the maximum increase of 1.6 K, located in Hubei, Sichuan, and Chongqing. The temperatures rise by 0.4 K over south Tibetan Plateau and the Hetao area, which are relatively limited. In winter, the changes in large-scale circulation background result in enhanced temperature over East Asia, which becomes bigger with increase of latitude. The temperature increases.

Fig. 9. Land use and vegetation of the MM5 model in the PD (a) and the mid-Holocene (b). The categories are: 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 forest, 13 evergreen broadleaf forest, 14 evergreen needleleaf forest, 15 mixed forest, 16 water bodies, 17 herbaceous wetland, 18 wooded wetland, 19 barren or sparse vegetation, 20 herbaceous tundra, 21 wooded tundra, 22 mixed tundra, 23 bare ground tundra, and 24 snow or ice.
Fig. 10. Temperature changes (K) resulted from vegetation change for (a) annual mean, (b) winter (DJF), and (c) summer (JJA).

Fig. 11. Precipitation difference (mm day$^{-1}$) resulted from vegetable change between the mid-Holocene and the PD.

a little over south Tibetan Plateau. There are two high centers with the maximum of 1 and 2 K, located in Jiangsu-Zhejiang and Xinjiang, respectively. In summer the changes in large-scale circulation background lead to temperature increase over most of East Asia, but temperature reduces over east Inner Mongolia and north India. Two high centers of temperature increases appear in southwest Xinjiang and Henan-Anhui, with the maximum of 2 and 3.5 K, respectively.

Figure 14 illustrates precipitation pattern due to the LCB changes. The changes in the large-scale circulation lead to precipitation increase over Northeast China, North China, northwestern China, and southwest Tibetan Plateau. Meanwhile, precipitation reduces over southern China. The precipitation increases are the most significant over east Inner Mongolia with a maximum of 1 mm day$^{-1}$. A high center of precipitation increase occurs over the Tibetan Plateau and north Xinjiang with a maximum of 0.5 mm day$^{-1}$. The precipitation decreases are the biggest in middle and low reaches of the Yangtze River with 0.5 mm day$^{-1}$. The 850-hPa wind vectors (Fig. 15) indicate that the winter monsoons become obviously weaker over eastern China because of the LCB changes. In summer, easterly and southerly winds strengthen over eastern China and north of the Yangtze River, so the effects from the Pacific Ocean enhance. The winds change insignificantly over South, Central,
Fig. 12. Changes in 850-hPa wind field resulted from vegetation change between the mid-Holocene and the PD for (a) January and (b) July.

Fig. 13. Temperature changes (K) resulted from change of large-scale circulation background for (a) annual mean, (b) winter (DJF), and (c) summer (JJA).

and Southwest China. The role of the South China Sea becomes weaker, and that from West Pacific Ocean strengthens to a small extent. The precipitation changes accord with the wind changes.

5. Summary

From the above, in the mid-Holocene, the changes of earth orbital parameters have little influence on mean annual temperature over China. However, the influences on the temperature in each season are different, which leads to the temperature decrease in winter and increase in summer. The changes of earth orbital parameters further result in obvious precipitation increases over North China and Northeast China with a maximum of 0.25 mm day$^{-1}$. This precipitation contribution is about 25% of total precipitation changes. CO$_2$ concentration is lower in the mid-Holocene than that in the PD, which brings about the temperature decrease. The effects of CO$_2$ on the climate vary with
Fig. 14. Precipitation changes (mm day$^{-1}$) resulted from changes in large-scale circulation background.

Fig. 15. Changes in 850-hPa wind field resulted from change of large-scale circulation background for (a) January and (b) July.

seasons, but the effects are limited.

During the mid-Holocene, vegetation distribution also transits along with the climate change. Because of the warm climate, plants in tropic and temperate climate zones gradually shift northward, and plants in frigid climate zones reduce gradually. This affects temperature significantly. The mean annual temperature enhances with a maximum increase of 0.8 K. In winter, the temperature increases with a warm center in South China. In summer, temperature enhances with a maximum increase of more than 1 K over Anhui. Meanwhile, precipitation increases over China. The significant increases occur in North China, south Tibetan Plateau, and Sichuan with a maximum increase of 0.25 mm day$^{-1}$. This precipitation contribution is more than 25% of total precipitation changes. The changes in the large-scale circulation background influence obviously the temperature and precipitation. This brings about temperature enhancing over China, and determines the main distribution feature of temperature changes, such as temperature increases in western and northern China, and a high center of temperature increase in between the Yellow and Yangtze River. The changes that in the large-scale circulation background control the precipitation changes. The precipitation changes over southern China are absolutely determined by the LCB with the maximum decrease of 0.5 mm day$^{-1}$, and over northern China mostly, they are controlled with a maximum increase of 1 mm day$^{-1}$ in east Inner Mongolia. The LCB precipitation contributes to about 50% of total changes over North and Northeast China.

The sensitivity experiments performed in this study enable us to further understand the mid-Holocene regional climate of China. The results indicate that the changes of air temperature, winds, and precipitation are primarily caused by LCB changes; then influenced by land-use and vegetation changes. The effects of earth orbital parameter change at LGM are equal to the role of vegetation in the mid-Holocene. The effects of CO$_2$ concentration on the climate are limited. In conclusion, over China, the relative mid-Holocene climate responses to different mechanisms from strong to weak are: large-scale circulation background, vegetation, earth orbital parameter, and CO$_2$ concentration.

The comparison of model results and geological records illustrates that the model is able to reproduce main features of climate in the mid-Holocene, especially in simulation of precipitation change. The MM5 results are better than CCM3 results. Relative to previous studies (Chen et al., 2002; Wang, 2002; Zheng
et al., 2004), the modeled precipitation changes are better, and consistent with lake records. However, model results in some places do not agree with geological records. Chen et al. (2004) found that drought occurs over Heihe and Shiyang River basins within the Qilian Mountain and Alashan region during the mid-Holocene. This is resulted from the precipitation decreases over the Qilian Mountain. The MM5 model does not reproduce precipitation decrease over the Qilian Mountain. But the model results indicate that the precipitation decreases over the south Huangtu Plateau and the surroundings of the Tibetan Plateau, where the precipitation reduces from geological records (Chen et al., 2004). This illustrates that the model results match with geological records. From the model results, it is found that these places are in near boundary from the precipitation increase to the decrease. The model precipitation changes are not exactly consistent with the geological records, so it is possible that precipitation reduces in the mid-Holocene. Based on the drought phenomenon, Chen et al. (2004) suggested that the summer monsoon declines. We think that it is incorrect. Model results suggest that the summer monsoon strengthens in the mid-Holocene in north of 30°N over eastern China, but the precipitation increases appear in north of 35°N. The precipitation increases happen in regions where water vapor convergence increases.

REFERENCES


