Modeling the East Asian climate during the last glacial maximum

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Abstract Using the CCM3 global climate model of National Center for Atmospheric Research (NCAR), this paper comparatively analyzes the characteristics of East Asian monsoon and surface water condition and the expansion of glacier on the Qinghai-Xizang (Tibetan) Plateau (QXP) between the present and the last glacial maximum (LGM). It is found that the winter monsoon is remarkably stronger during the LGM than at present in the north part of China and the western Pacific but varies little in the south part of China. The summer monsoon remarkably weakens in South China Sea and the south part of China during the LGM and has no remarkable changes in the north part of China between the present and the LGM. Due to the alternations of the monsoons during the LGM, the annual mean precipitation significantly decreases in the northeast of China and the most part of north China and the Loess Plateau and the eastern QXP, which makes the earth surface lose more water and becomes dry, especially in the eastern QXP and the western Loess Plateau. In some areas of the middle QXP the decrease of evaporation at the earth surface causes soil to become wetter during the LGM than at present, which favors the water level of local lakes to rise during the LGM. Additionally, compared to the present, the depth of snow cover increases remarkably on the most part of the QXP during the LGM winter. The analysis of equilibrium line altitude (ELA) of glaciers on the QXP, calculated on the basis of the simulated temperature and precipitation, shows that although a less decrease of air temperature was simulated during the LGM in this paper, the balance between precipitation and air temperature associated with the atmospheric physical processes in the model makes the ELA be 300—900 m lower during the LGM than at present, namely going down from the present ELA above 5400 m to 4600—5200 m during the LGM, indicating a unified ice sheet on the QXP during the LGM.

Keywords: last glacial maximum, climatic simulation, East Asian monsoon, glacier on the Tibetan Plateau.

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Climatologists have been paying much attention to the global and regional climatic characteristics during the LGM. A lot of paleodata were obtained in East Asia during the LGM[1—5] and laid the firm foundation of reconstructing East Asian paleoclimate through climatic models. Using the atmospheric general circulation model (AGCM) with an SSIB land surface process and the horizontal resolution of 7.5° × 4.5° and nine vertical levels, Chen et al.[6] (hereafter called CH20) simulated the climatic features in China during the LGM and showed that annual mean of surface air temperature in the mainland of China to the south of 40°N is generally 3℃ lower during the LGM than at present, with more precipitation and wetter soil in the Loess Plateau and the north and northeast parts of China during the LGM, indicating a cold and wet climate in these areas. Afterwards, Yu et al.[7] (hereafter called YU20) also employed this climatic model to further examine the East Asian climate during the LGM. Compared to the results of CH20, YU20 simulated the same distribution of precipitation in East Asia and found that the decrease of air temperature in north China and the east part of northwest China was much sharper, which throws a doubt about the results of the model. It should also be noticed that the cold and wet climate in the north part of China during the LGM, simulated by CH20 and YU20, is evidently not consistent with the phenomena revealed by a lot of paleodata[3—5].

As we know, studying the mechanisms for paleo-climatic variations is based upon reconstructing paleoclimate. Therefore, it is necessary to do more researches on the East Asian climate during the LGM, e.g. reasonably reconstructing the paleoclimate and carefully analyzing winter and summer monsoons in East Asia and their effects on climates and environments. Using the CCM3/NCAR global climate model[8], this paper simulates the climatic characteristics of winter and summer monsoons and surface water conditions in East Asia and glacial areas on the QXP during the LGM and at present.

1 Model and data

The CCM3 climate model with the horizontal resolution of 2.8° × 2.8° and eighteen vertical levels includes complicated physical processes between land and air and considers the effects of atmospheric water vapor and CO_2 content on radiation. Two experiments, one for the present and the other for the LGM, are designed in this paper. For the present experiment, the original CCM3 model[8] was run. For the LGM experiment, the eccentricity and obliquity and longitude of perihelion are 0.018994 and 22.949° and 114.425°, respectively, and global distributions of surface conditions and ice sheets come from CLIMAP's[9] and Peltier's[10] reconstructions. Sea surface temperature is from Wang's paleodata in South China Sea and the western Pacific[1] and from CLIMAP's datasets in the other areas. Because the data of sea surface temperature during the LGM have only the values in February and August, the time interpolation with the sine function was applied so as to obtain sea surface temperature in the other months. In the LGM experiment, we also utilized the paleo-vegetation conditions in East Asia[11] and present vegetation types in the other areas. The topography during the LGM is the same as the present one. In the LGM and the present experiments, the CO_2 levels are 200 ($\times 10^{-6}$) and 345 ($\times 10^{-6}$), respectively. Under the above-mentioned conditions, the CCM3 model was integrated for twenty-five years from the initial time of the original model in the present and LGM experiments, respectively, and the mean value over the last ten years was used in analyzing climatic features. The significance of climatic difference between the LGM and the present was checked up through the Student's t-test.

In order to realize the modeling capability of the CCM3 model in East Asia, the comparison between the surface air temperature in the present experiment and the observed one averaging from 1961 to 1990 on the basis of NCEP reanalysis datasets[12] shows that the simulated annual mean temperature between 100°E and 120°E approaches the observed one and the difference between them is smaller than 1℃ (figure not shown). Furthermore, the model simulates successfully the rainfall pattern of East China in July, with heavy rainfall (> 200 mm) appearing to the north of the Changjiang River and less rainfall appearing to the south. All these show that this model has the capability of capturing the major characteristics of temperature and precipitation in East Asia and may be applied to climatic simulation in East Asia.

2 Monsoon and temperature during the LGM

Fig. 1(a) shows the difference of 850 hPa wind between the LGM and the present and the statistic confidence of the difference of wind component (v) in the north-south direction. Fig. 1(a) detects that the anomalous northwesterly prevails over the East Asian continent and the Pacific between 100°E and 150°E, especially over the East Asian coasts where the continental shelf greatly varies between the LGM and the present, and the difference is remarkable (exceeding the 95% confidence level, hereafter called CL) in the north part of China and the western Pacific and eastern Siberia, indicating a remarkably strong winter monsoon and more frequent activities of cold air masses during the LGM. The difference of v component does not exceed the 90% CL in the south part of China, indicating the little change of winter monsoon between the LGM and the present. In July (fig.1(b)), the anomalous northerly is remarkable in south China and South China Sea and the low latitudes of the western Pacific (exceeding the 95% CL) whereas it is not significant in the north part of China. On the whole, the remarkably anomalous northerly appears in the belt from Arabian Sea to the

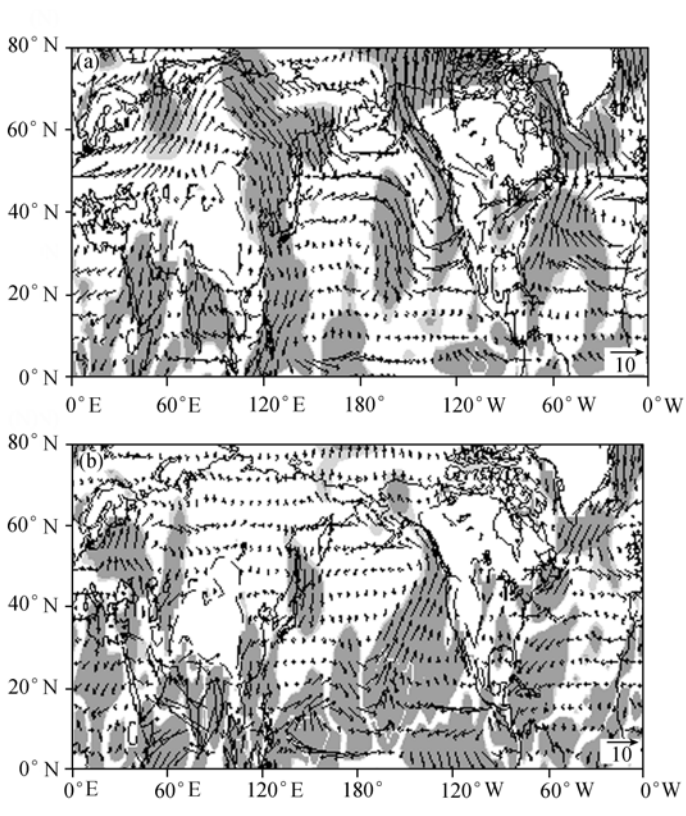

Fig. 1. The difference of simulated 850 hPa wind (m/s) between the LGM and the present in January (a) and July (b) (heavy and light shaded areas denote the 95% and 90% CLs of v difference between the LGM and the present, respectively; the thick dashed line denotes the topographic contour of 1500 m).

southern Sea of Okhotsk via south China, suggesting that summer monsoon weakens in these areas during the LGM, especially in the south part of China and South China Sea (exceeding the 95% CL), and the summer monsoon varies little in the north part of China. The strong winter and weak summer monsoons during the LGM make more cold air masses in winter and less warm ones in summer invade East Asia, and cause surface air temperature to go down. Compared to the present, the annual mean temperature decreases by 3℃—6℃ in the northeast part of China, over 5°C in the eastern coasts of China, 3℃—4℃ in the northwest of China, and 2 ℃—4℃ in the QXP and South China Sea (fig. 2). All of these temperature differences exceed the 95% CL.

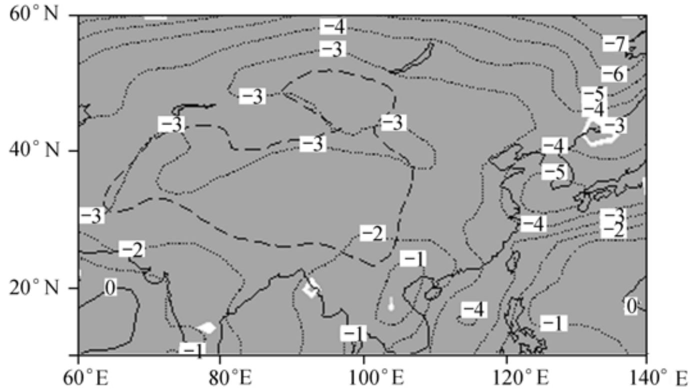

Fig. 2. The difference of simulated annual air temperature (℃) between the LGM and the present (heavy and light shaded areas denote the 95% and 90% CLs of the difference, respectively; the thick dashed line denotes the topographic contour of 1500 m).

3 Precipitation and budget of surface water during the LGM

Fig. 3(a) shows the difference of simulated annual mean precipitation between the LGM and the present in East Asia. Compared to the present, the precipitation decreases in the most part of East Asia during the LGM, with the decrease of the precipitation going beyond 0.5 mm/d (namely total precipitation of 180 mm in a year) in the eastern QXP and the Loess Plateau and north China (exceeding the 95% CL). The precipitation decreases by 0—1 mm/d in the most part of northeast China and 0—0.5 mm/d in Uygur Autonomous Region of Xinjiang. But the precipitation increases in some areas of the southwestern QXP during the LGM, with its maximal value being about 0.5 mm/d (exceeding the 95% CL). The precipitation difference does not go beyond the 90% CL in the south part of China between 25°N and 30°N and in the most part of the middle and western QXP areas, which shows that there are no remarkable differences between the LGM and the present in these areas. In order to conveniently discuss surface water conditions in East Asia, the difference of precipitation from surface evaporation is defined as surface water budget in this paper. On the annual average (fig. 3(b)), the difference of the water budget between the LGM and the present is negative in the eastern and northeastern QXP areas, the Loess Plateau, North China, and the most part of Northeast China (exceeding the 95% CL) and the maximal negative difference appears in the eastern QXP and the western Loess Plateau, indicating that surface soil loses water

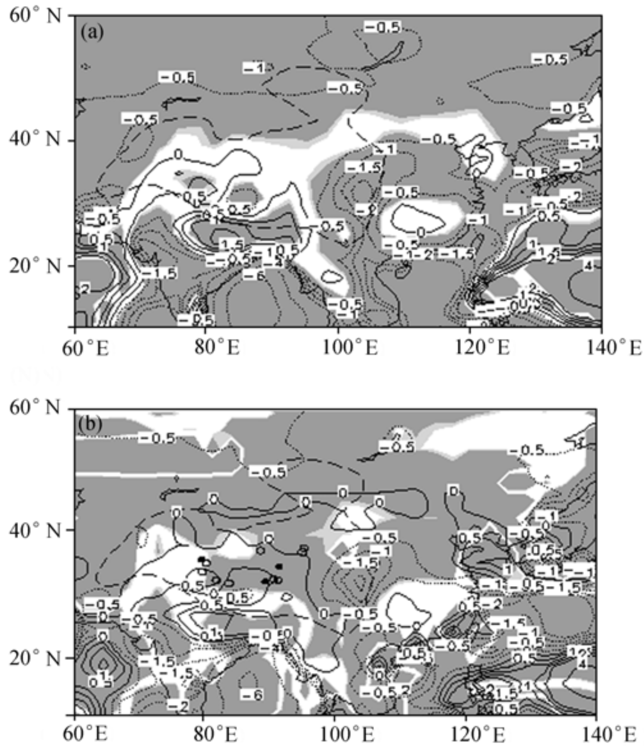

Fig. 3. (a) The difference of simulated annual mean precipitation (mm/d) between the LGM and the present (heavy and light shaded areas denote the 95% and 90% CLs of the difference, respectively; the thick dashed line denotes the topographic contour of 1500 m), (b) the difference of simulated annual mean surface water budget (mm/d) between the LGM and the present (heavy and light shaded areas denote the 95% and 90% CLs of the difference, respectively; the black dot denotes the position with a high water level of a lake and the open circle denotes the position with a middle water level[13]; the thick dashed line denotes the topographic contour of 1500 m).

and becomes dry during the LGM. Being opposite to this, the positive difference of 0—0.5 mm/d occupies the most part of the middle and western QXP areas between 80°E and 95°E (exceeding the 95% CL), showing that the soil obtains water and becomes wet during the LGM. Compared to the difference of precipitation shown in fig. 3(a), it is easy to see that during the LGM the loss of the soil water is mainly caused by the decrease of precipitation in the eastern QXP and the Loess Plateau and North China. For the most part of the middle QXP with the positive difference of the water budget, the precipitation decreases (exceeding the 95% CL) or has no remarkable increase. In these areas, therefore, the wetter soil during the LGM results mainly from the decrease of surface evaporation caused by the reduction of surface air temperature.

In summary, the strong winter and weak summer monsoons during the LGM change the precipitation and surface soil moisture in East Asia and result in less precipitation and more dry soil in the eastern QXP, the Loess Plateau, and the north and northeast parts of China. These results are in agreement with the evidences of paleodata. The paleodata show that annual precipitation remarkably decreases in the Loess Plateau, the north and northeast parts of China, the eastern QXP, and the most part of Uygur Autonomous Region of Xinjiang during the LGM[3] and the great decrease of precipitation appears in the valleys of the Huanghe River, to the north of the river, and Northeast China[4,5]. However, the precipitation during the LGM is 80% of the present one in the south part of China[3], indicating that the precipitation during the LGM is close to the present one. During the LGM, the area of active sand dune remarkably increases in the north part of China to the east of 105°E, and the north part of Uygur Autonomous Region of Xinjiang and sand dunes appear in the Jinsha and Nujiang Rivers being located in the eastern QXP[5], indicating less precipitation and more dry soil in these areas. In Tibet to the west of 90°E and the south part of China, the area of sand dunes varies little between the LGM and the present, indicating little changes in precipitation and soil water content. Based on the paleodata of lakes in China, Yu et al.[13] addressed wetter surface soil and higher water level of lakes in the QXP during the LGM. Through comparing the result of Yu et al. with the simulated one in the QXP (fig. 3(b)), it is seen that most stations with the middle or high water levels correspond to the positive or almost zero difference of the water budget between the LGM and the present, showing the simulated soil moisture approaches the evidence of Yu et al. Thus the simulated precipitation and surface soil moisture in this paper are in agreement with the paleo-climatic evidences and remarkably improve the simulations of CH20 and YU20.

4 Ice sheet on the QXP

Fig. 4(a) shows the difference of simulated winter depth of snow cover between the LGM and the present. Owing mainly to the increase of snowfall (figure not shown) during the LGM, the depth of snow cover remarkably increases in the southern QXP during the LGM and increment is bigger than 100 mm in the southwestern QXP (exceeding the 95% CL), which provides a favorable condition for the expansion of glaciers on the QXP during the LGM. However, there is a heated argument about the existence of a unified ice sheet on the QXP during LGM[14,15]. It is well known that the decreases of precipitation and temperature directly affect the glacial area of the QXP. Based on simulated air temperature and precipitation in the LGM and the present experiments, the glacial area of the QXP will comparatively be analyzed in the following section.

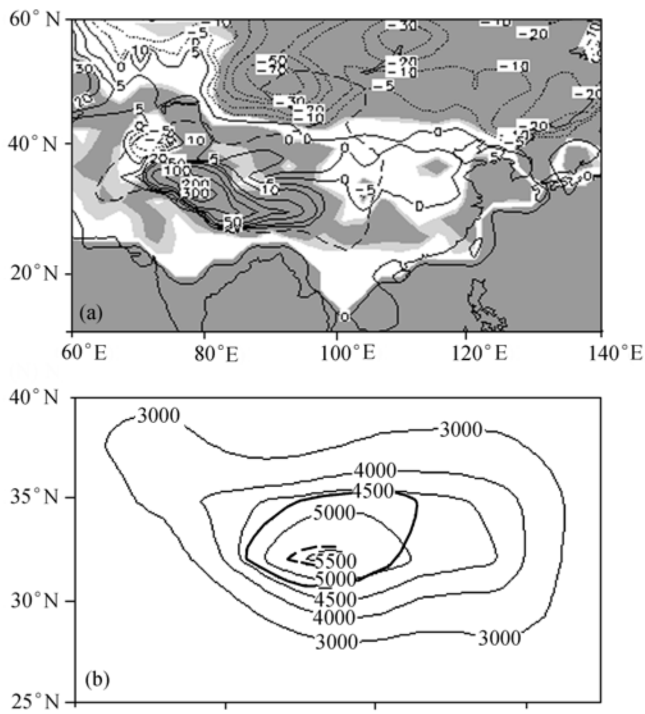

Fig. 4. (a) The difference of simulated winter mean depth (mm) of snow cover between the LGM and the present (heavy and light shaded areas denote the 95% and 90% CLs of the difference, respectively; the thick dashed line denotes the topographic contour of 1500 m), (b) the ELA of simulated glacier on the QXP (the thick solid line stands for the LGM, the thick dashed line the present; and the thin solid line the topographic elevation (m)).

Shi et al.[16] showed the relationship between summer (JJA) mean temperature and annual total precipitation at the ELA of glacier in western China as follows:

$$T_{s0} = -15.4 + 2.48 \times \ln P_r,$$

where the T_{s0} denotes the critical value of summer mean air temperature (℃), P_r the annual total precipitation (mm). When the summer mean air temperature is lower than T_{s0} in some place of the QXP, glacier locally piles up and its area expands; and vice versa.

Although the thick horizontal resolution and smooth topography in the CCM3 model possibly make the simulated glacial area differ from the observed, it is acceptable to compare all the alternations of the glacial area between the LGM and the present by using the simulated data. Fig. 4(b) shows the calculated ELAs from simulated precipitation and temperature during the LGM and at present. The present ELA goes beyond 5400 m on the QXP, corresponding to a small-scale glacial area. But during the LGM the ELA is between 4600 m and 5200 m and decreases by 300—900 m in comparison with the present. The reduction of 700—900 m occurs in the north and west parts of the QXP and the decrease of about 300—400 m appears in the east part. Evidently, the glacial area is much larger during the LGM than at present. Because the QXP has the mean topographic elevation of 5000 m during the LGM, it is easy to see that a unified ice sheet develops on the QXP during the LGM. It should especially be noticed that the difference of the simulated annual mean air temperature on the QXP between the LGM and the present is only 2℃—4℃, much less than the one pointed out by Liu[14] and Shi[15] on the basis of paleodata. Despite of the little difference of the temperature in the model, the simulated precipitation varies correspondingly during the LGM due to the balance between the temperature and precipitation associated with atmospheric physical processes in the model, which still makes the glacier expand and a unified ice sheet form on the QXP during the LGM.

5 Conclusion and discussion

Numerical simulations show that the winter monsoon is remarkably stronger during the LGM than at present in the north part of China and the middle and low latitudes of the western Pacific and the summer monsoon is remarkably weaker during the LGM than at present in South China Sea and the south part of the mainland of China, which results in the decrease of air temperature in East Asia during the LGM. Meanwhile, the precipitation also decreases in the most part of East Asia during the LGM, especially with the greatest decrease in the eastern QXP and the Loess Plateau and North China, which makes the earth surface soil lose water and become dry during the LGM. Because of the little variation of annual precipitation and the decrease of surface evaporation caused by the reduction of air temperature in the most part of the middle QXP, the surface soil loses less water and becomes wetter during the LGM than at present, favoring the water level of local lakes to rise during the LGM. This process may explain why the water level of the lakes in the middle QXP is higher during the LGM than at present. Additionally, during the LGM, the depth of snow cover remarkably increases on the QXP mainly due to the increase of snowfall during winter, which favors the formation and expansion of glacier. As a result of the balance between precipitation and air temperature in the model, the ELA of glacier on the QXP is 300—900 m lower during the LGM than at present, namely going down from the present ELA above 5400 m to 4600—5200 m during the LGM, which indicates the existence of a unified ice sheet on the QXP during the LGM from the view of climatic simulation.

We should also pay attention to the fact that analogous to previous simulations[17,18], the difference of simulated East Asian air temperature between the LGM and the present in this paper is less than the paleo-climatic evidence. Because simulated air temperature approaches the observed for the present climate, the simulated higher temperature during the LGM is mainly responsible for the little difference of the simulated temperature between the LGM and the present. Studies also show that the difference between Wang's and CLIMAP's sea surface temperature during the LGM may make annual mean temperature increase or decrease by 0℃—2℃ in East Asia. But Jiang et al.[18] found out that if a suitable area of ice sheet appears on the QXP during the LGM, lower air temperature is simulated in East Asia and the extra decrease of the temperature during the LGM exceeds 5°C in the QXP. Just as pointed out by Liu et al.[14], the changes of QXP environments during the glacial period possibly have significant effects on monsoon climate. However, it is necessary to do more researches on the doubt whether it is the realistic temperature or the simulated one that is higher during the LGM. No matter how the matter goes, the doubt is closely associated with paleodata. This is also a problem that should urgently be solved in simulating the East Asian climate during the LGM.

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