SENSITIVITY EXPERIMENTS ON INFLUENCES OF UPLIFT OF QINGHAI-XIZANG PLATEAU ON CIRCULATION IN SUMMER*

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ABSTRACT

A coupled general circulation model in a zonal belt is used to simulate the variation of circulation features in the process of uplift of the Qinghai-Xizang Plateau. The results reveal that the heating rates of the Plateau increase with the rising of the Plateau topography, and the latent heating component in the heating field tends to be the most important heating factor. The uplift of the Plateau enhances the upward motion, intensifies the pressure systems in the high and low level atmosphere, reinforces Southeast Asia monsoon strength, increases precipitation and severely decreases the surface temperature over the Qinghai-Xizang Plateau.

However, the basic structures of the general circulation do not vary much due to the uplift of the Qinghai-Xizang Plateau, and it is the land-sea distribution that is the decisive factor to form the present circulation pattern and monsoon. Therefore, to simulate the paleoclimate during the geological period people should consider more factors, especially the land-sea distribution.

Key words: uplift of Qinghai-Xizang Plateau, general circulation, sensitivity experiments, climatic change

I. INTRODUCTION

The Qinghai-Xizang Plateau with mean elevation above 4000 m is the highest and steepest one in the world. Many studies proved that the Qinghai-Xizang Plateau had remarkable influences on the circulation systems and the surrounding climate through its thermal and dynamic forcing. But the study results are not consistent with one another about the extent of influences of the Plateau.

Since 1960s, many scientists have simulated the climatic effects of orography by GCM as Hahn et al. (1975), Barron and Washington (1984), and Kutzbach and Guetter (1989). But these research results all overestimated the influences of the Plateau. Qian et al. (1988) has used 2 and 5 layer regional climatic models to simulate the influences of the Qinghai-Xizang Plateau on the East Asia circulation and climate since 1975. They put their focus on the treatments of steep terrain in the model, and developed a limited area model with p-sigma incorporated coordinate system to deal with the topography. The model highest orographic elevation is more than 5 000 m, and the terrain gradient is also larger. The DDD scheme of coordinate transformation is used to calculate the pressure gradient force in the complex terrain area. Kuo

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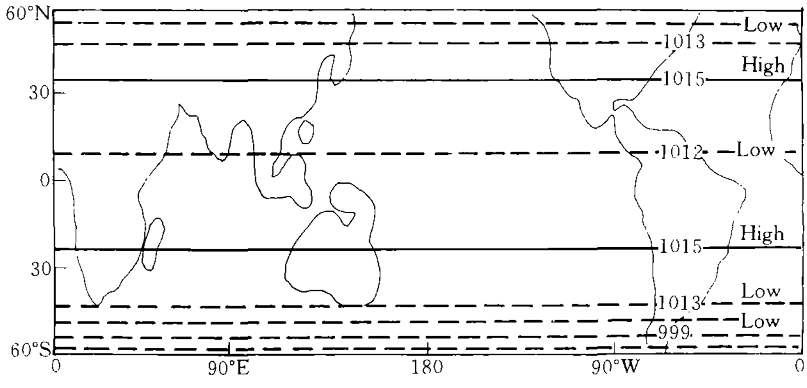

Fig. 1. Initial sea-level pressure distribution.

and Qian (1982) first simulated the effects of the Plateau on monsoon and pointed out that such effects had the secondary importance while the land-sea distribution had the first. Recently Qian et al. (1994) emphasized the sea and land thermal forcing again by numerical experiments. But the model used in Qian' s experiments is too simple and confined in a limited area. In order to avoid the east-west lateral boundary problem and the oversmooth of the terrain such as in the spectral model, in this paper, based on above research work, a coupled general circulation model system in a zonal belt (60°N—60°S) is used to simulate the variation of the circulation and climatic features in the process of uplift of the Qinghai-Xizang Plateau.

II. THE MODEL SYSTEM

The model system used in this paper is a land-air and air-sea coupled model system, in which the atmospheric model is a 5-layer primitive equation model with p-σ incorporated coordinate system in the vertical. It includes various diabatic and adiabatic physical processes, moreover the shortwave solar radiation contains the diurnal variation. The mixing layer ocean model has two layers, and the thicknesses are 50 m and 250 m, respectively (see Qian 1992). The soil model also has two layers, the first soil layer is thinner and reflects the diurnal changes of the soil temperature and moisture. The second layer is thicker and represents the annual variations. Only one sort of 6 underlying surfaces of the model (clay pasture) is used in this paper.

The model system has a zonal domain between 60°N and 60°S, the horizontal grid network is spherical one with a grid size of 5° lat. $\times$ 5° long., the time step is 15 min. The initial fields used in the model are the multiyearly zonally averaged geopotential height fields at 100, 300, 500, 700 hPa levels and sea level pressure field (Fig. 1) and the mixing ratio fields at 300, 500, 700 and 850 hPa levels in June. After initialization, the temperatures, the geopotential height and the velocity components can be obtained, and the surface pressure can be gotten by interpolation. A time integration of 5 model days is first made and a quasi-stationary state is reached with little changes of the model variables, then another 15-d integration is further made, analyses and discussions are made for the mean climate state in summer in the last 15 days. The land-sea distribution in the model and the topography in the control experiment are close to the real ones.

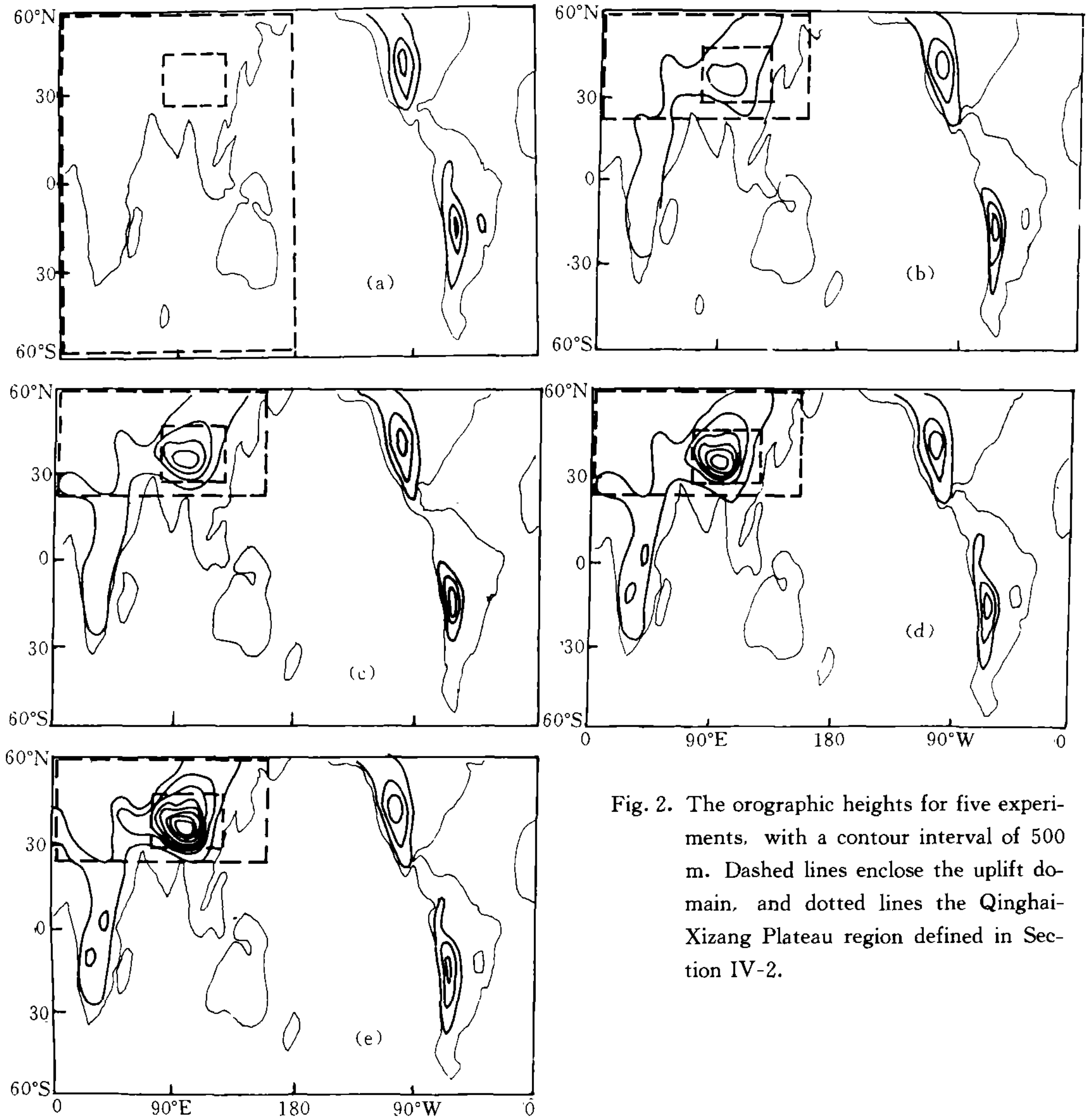

Fig. 2. The orographic heights for five experiments, with a contour interval of 500 m. Dashed lines enclose the uplift domain, and dotted lines the Qinghai-Xizang Plateau region defined in Section IV-2.

III. EXPERIMENTAL SCHEMES

Five experiments are designed according to different elevations of the Qinghai-Xizang Plateau and its surrounding areas during the process of uplift of the Qinghai-Xizang Plateau (see Table 1). EM100 designates the control experiment with the real orography. Except for the orographic heights, the lower boundary conditions and the physical parameters do not change in various experiments. Figures 2a—2e show the orographic patterns of the five experiments, respectively.

Table 1. Experimental Schemes

Code name	Uplift domain	Model orographic heights (m)	
1 EM0	60°N—60°S 0°E—180°E	$h=h_0$	
2 EM25	60°N—20°N	$h=h_0$	$h_0\leqslant 500$
	0°E—145°E	$h=500+0.25(h_0-500)$	$h_0>500$
3 EM50	same as 2	$h=h_0$	$h_0\leqslant 500$
		$h=500+0.5(h_0-500)$	$h_0>500$
4 EM75	same as 2	$h=h_0$	$h_0\leqslant 500$
		$h=500+0.75(h_0-500)$	$h_0>500$
5 EM100		$h=h_0$	

Note: In Table 1, h_0 represents the real orographic elevation, and h the elevation used in the different experiments.

IV. EXPERIMENTAL RESULTS

1. *Simulation Results of the Control Experiment* (*EM*100)

Figures 3 show the sea level pressure distributions (Fig. 3a) and the 200 hPa level streamlines (Fig. 3b), the upper one is simulated by the model and the lower the corresponding observation. The main structure of the simulated climatic fields is relatively consistent with the observed one. However, it is found that the strengths of the subtropical highs over the Pacific and the Atlantic Oceans are slightly weaker. It may be due to the homogeneous soil type used in the control experiment. At the 200 hPa level (Fig. 3b), the simulated anticyclonic circulation over the North America is too strong. However it is still weaker than the Qinghai-Xizang Plateau high which can be proved by the height field map (omitted). The simulated atmospheric temperature, the mean land surface temperature, humidity, rainfall etc. are also comparable with the observational results.

2. *The Variations of the Atmospheric Heating Status over the Plateau*

It is assumed that the Qinghai-Xizang Plateau can be represented by an area inside 25—45°N, 70—115°E. Table 2 shows the changes of the orographic elevation in the five experiments.

In the whole atmospheric column over the Plateau, the total diabatic heating rate (Q) is the sum of latent heat rate (LP) due to condensation, radiative heating rate ($R+I$) including the solar radiative (R) and the longwave radiative (I) heating, and the turbulent diffusive heating rate (S) (including the sensible heat), all the units for heating rate are ℃/d.

Figure 4 reflects that the atmospheric diabatic heating rate and each component over the Plateau with increasing elevation. It is shown that the latent heating term is the most principal

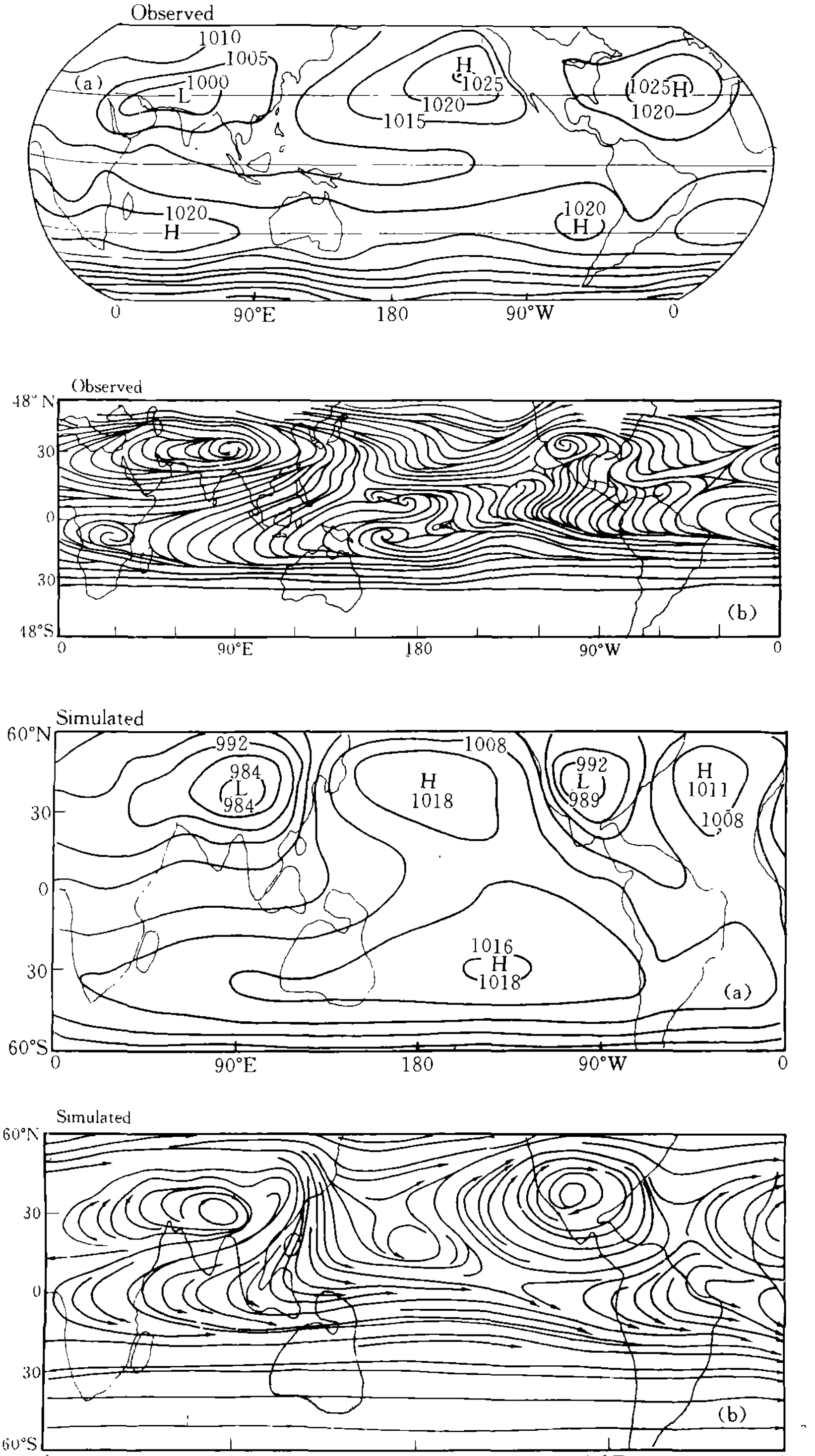

Fig. 3. The simulated and the observed sea level pressure (a), 200 hPa streamlines (b).

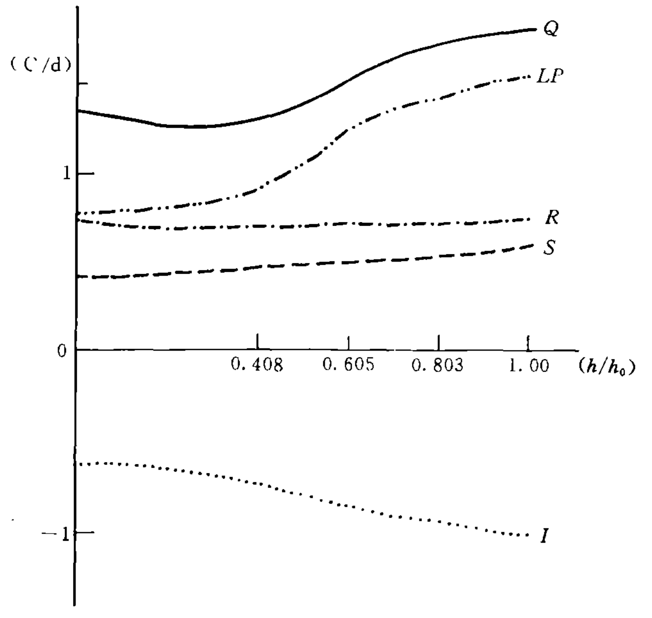

Fig. 4. Changes of the diabatic heating rate and heat components with increasing elevation.

term among the heat components, and then sequentially are I, R and S. $R+I$ is usually negative, indicating that the atmosphere over the Plateau is generally cooled due to radiation. Q is always positive, indicating that the Qinghai-Xizang Plateau is an atmospheric heat source in summer. The simulated heating rates are fairly in agreement with that estimated by Luo and Yanai (1984). Their results are as follows: $Q=157$ W/m^2, $LP=134$ W/m^2, $S=96$ W/m^2, $R+I=-73$ W/m^2.

Table 2. Average and Maximum Elevations in the Vicinity of the Qinghai-Xizang Plateau Region in Five Experiments (Unit: m) *

	EM0	EM25	EM50	EM75	EM100
Average elevation	10 (0.004)	957 (0.408)	1420 (0.605)	1882 (0.803)	2345 (1.00)
Maximum elevation	10 (0.002)	1591 (0.327)	2683 (0.551)	3774 (0.776)	4866 (1.00)

* The average elevations are computed for 36 grid squares inside the region 25—45°N, 70—115°E. The value in parentheses indicates the fractional elevation (compared to EM100).

Table 3. Average Land Surface Temperature (T_s) and Average Rainfall (P) in the Vicinity of the Qinghai-Xizang Plateau Region in Five Experiments

	EM0	EM25	EM50	EM75	EM100
T_s (℃)	38.45	34.26	31.75	29.05	27.00
P (mm/d)	1.523	1.525	2.024	2.173	2.339

In the process of uplift of the Qinghai-Xizang Plateau, Q gradually rises from EM25 to

EM100. but the increasing speed decreases. The change of *LP* is very analogous to the *Q*. *I* is always negative and becomes less and less with the elevation increasing. The varying range of *R* is not large. so the variation of $R+I$ principally depends on the *I*. *S* is also increasing gradually. From EM0 to EM100, *Q* increases by 36 per cent, so in the progressive uplift of the Plateau the heating effect is continuously increasing and mainly because of the increasing latent heat. There is an only exception from EM0 to EM25, it may be due to that the orographic uplift domain for EM0 is different from other experiments.

Table 3 shows that the average land surface temperature (T_s) and the rainfall (*P*) change with the increasing elevation. With the Plateau uplift, from EM0 to EM100, T_s severely drops 11. 45°C averagedly. However the rainfall increases, and its increasing tendency is agreement with the LP.

3. *Vertical Motion* (500 *hPa*)

Vertical motion patterns at the 500 hPa in the five experiments show that there are always the upward motions over the land, especially over the Southeast Asia, the North Africa and the Mexican Gulf, and there are always the downward motions over the oceans, except for the tropical Pacific area and its west boundary where the upward motion dominates. In the EM0, due to the removed orography and the homogeneous underlying surface, the local circulation and the vertical motion are weaker, the maximum rising motion area is over the Western Hemisphere where the real orography is adopted. With the Plateau uplift, the heating effect of the Plateau on the atmosphere increases, the rising motion in the vicinity of the Plateau aggravates. The domains of the upward and the downward motions have not changed essentially.

4. *Boundary Layer Winds and the Sea Level Pressure Field*

The sea level pressure field and the boundary layer wind field (Fig. 5a) are analysed. It is found that there are two anticyclonic circulations over the Eurasia and the North America, and two cyclonic circulations over the Pacific and the Atlantic either in EM0 and EM25 where the orography is relative smooth or in EM75 and M100 where the orography is high. The low-level cyclonic circulation over the Plateau region strengthens obviously with the increasing elevation. It is shown in Fig. 5b that the strengthening of the Plateau heating rates makes the airflow in the surrounding area of the Plateau (especially to its east and south parts) converges cyclonically towards the Plateau, promoting the summer monsoon in East China to migrate northward.

Table 4. Changes of the Location and the Central Strength of the Plateau Low in Sea Level Pressure Field

	EM0	EM25	EM50	EM75	EM100
Longitude	98°E	94°E	92°E	91°E	90°E
Latitude	42°N	39°N	38°N	37°N	36°N
Central strength (hPa)	998	992	989	986	984

The changes of the sea level pressure with increasing elevation are illustrated in Fig. 6 and Table 4. The effect of increasing elevation forces the Asia continental low to move southward

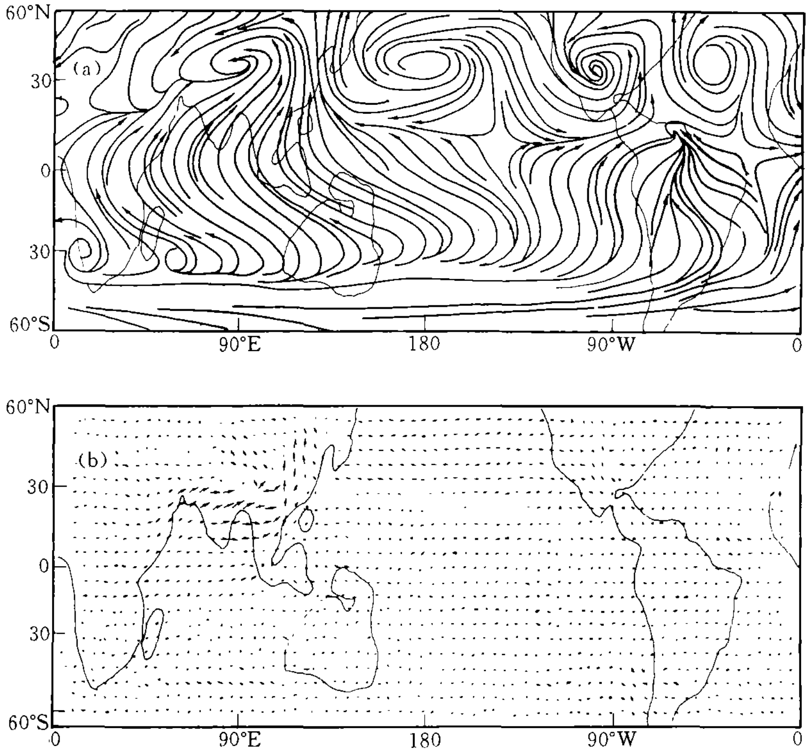

Fig. 5. Simulated boundary layer streamlines for EM0 (a), and simulated boundary layer wind differences (EM100−EM0) map (b).

and westward by 6 degrees of latitude and 8 degrees of longitude, respectively. At the same time, the intensity of the low enhances by 14 hPa. As a result, the Plateau uplift increases the south-to-north pressure gradient in the South Asia and enables the moist deflective southerlies coming from the Indian Ocean to enter far into the Plateau area. It also explains why the rainfall increases with the increasing orographic heights which is shown in Table 3.

5. *Upper Level Atmospheric Flow*

The basic patterns of the 200 hPa level streamline (Fig. 3) and heights are similar in the five experiments. In the mid and high latitudes of the Northern Hemisphere there are anticyclonic circulations over the land areas and cyclonic circulations over the oceans. However, because of the stronger heating effects of the land in summer, the anticyclonic circulations over the land have large domains and high intensities. There is no closed cyclonic circulation centre over the Atlantic Ocean due to its smaller oceanic area, while there is one over the Pacific Ocean.

By its comparison with the boundary layer flow field, it is found that the flow fields at the upper and the lower levels are in the opposite phase, it means that the circulation systems simulated by the model have apparent baroclinicity. Over the Southern Hemisphere the circulation pattern is simple, at the upper levels there are westerlies and at the lower levels there are westerlies, too, at the high latitudes, while deflective southerlies across the equator predominate at the mid and the low latitudes.

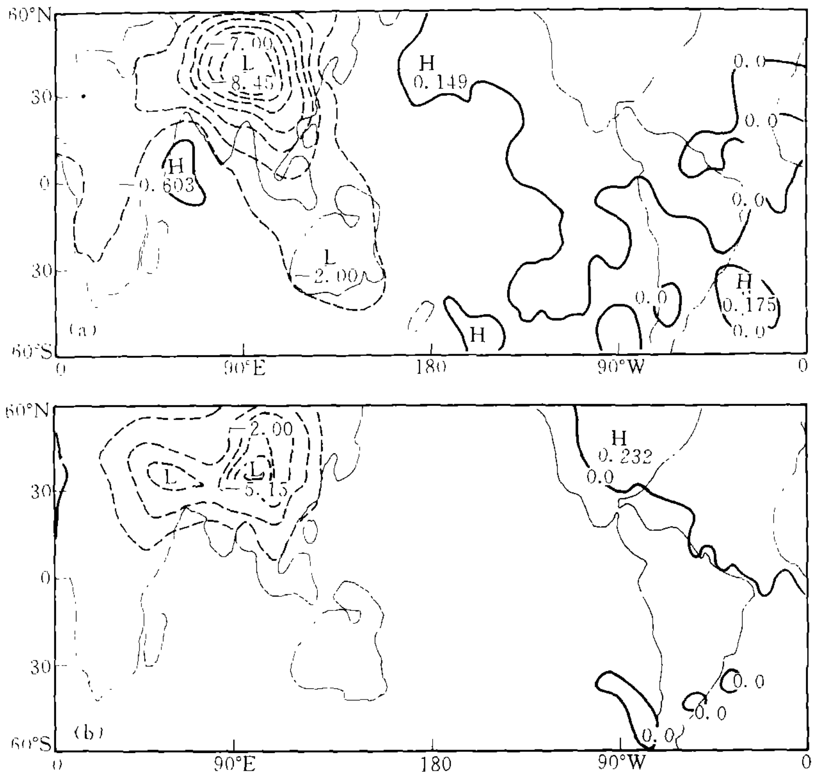

Fig. 6. Sea level pressure differences between EM50 and EM0 (a), and EM100 and EM50 (b): EM50−EM0, EM100−EM50.

The effects of the Plateau uplift on the upper level winds are consistent with the lower ones. It makes the continental high, which is located originally in the area to the north and the east of the Plateau before the uplift, migrate southeastward and then locate just over the Plateau, at the same time the intensity of the high enhances continuously.

Nevertheless, either before or after the uplift of the Plateau the circulation systems in the Northern Hemisphere have a two-wave zonal structure both at the upper and the lower levels. Such a zonal structure is very agreeable with that of the land and the sea distribution at the high and the mid latitudes of the Northern Hemisphere. It is proved, hence, that variations of the orographic heights can not fundamentally change the basic structures of the general circulation. Under the fixed solar radiative forcing, only the land-sea distributive pattern and the thermal difference between the land and the sea are the dominant cause in forming the morden general circulation and the summer monsoon. The topography in the globe is the secondary factor to circulation systems.

6. *Meridional Circulation*

The meridional circulation (V-W) profile figures along 90° E are shown in Figs. 7a and 7b. They reveal some features of the meridional circulations. With the smooth orography, because the circulation is mainly influenced by the thermal differences both between various latitudes and between the land and the sea, the meridional circulation pattern is simpler, the strength and the scope of the simulated monsoon circulation are both less than that of the

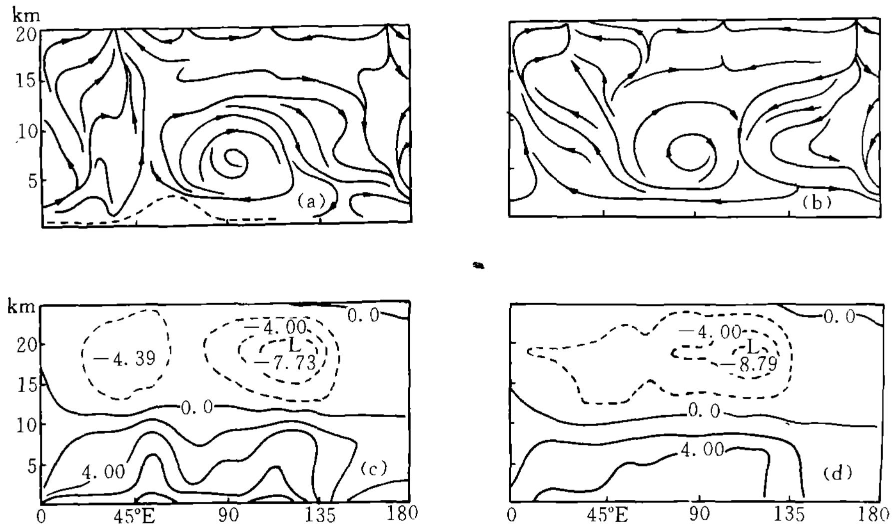

Fig. 7. Meridional circulation along 90°E in EM100 (a) and EM0 (b); and V-component vertical profile along 20°N in EM100 (c) and EM0 (d).

modern monsoon, the rising airflow over the Plateau is weaker, and the rainfall is less. With the Plateau uplift, because of the orographic effect, the circulation pattern becomes more complicated, the rising motion over the Plateau aggravates, the monsoon circulation strength on the south side of the Plateau enhances outstandingly, and the range extends, too. From 30°S to the Plateau, there are all the deflective southerlies across the equator in the boundary layer, and there is the sinking airflow on the north side of the Plateau. It is analogous to the Ye' s research results (1979).

Figures 7c and 7d show the V-component vertical profile maps along the 20°N in EM100 and EM0. It is found that the southerlies at the lower level stretch up to the 500 hPa, and are thicker in EM100. The southerlies reverse to the northerlies above the 500 hPa level. With the real orography, the strength of southerlies is obviously stronger than that in EM0. There are two maximum centres at 55°E and 115 ° E, respectively, matching with the maximum centres of the northerlies at the upper level, which form respectively independent vertical circulation systems. The southerlies have not obvious maximum centre in EM0, only northerlies have a relative high value centre at the upper level at 115°E. The longitudinal width of the southerlies and northerlies in EM100 is 10 degrees wider than that in EM0.

V. CONCLUSIONS AND DISCUSSIONS

In summer, because of the thermal difference between the land and the sea, the continent is the heat source and the ocean is the heat sink relatively. From the simulation results it is found that the orographic uplift substantially strengthens the continental features of the underlying surface, and induces more the effects of the heat sources, to which the contribution of the latent heating is of first importance, of the underlying surface on the atmosphere with the increasing orographic heights. At last the pressure systems in the high and the low level atmosphere are intensified, the positions further southward and toward the inner continent, the pressure gradient in the South Asia and the East Asia increases, both the strength and the width of the Southeast Asia monsoon increase. And it causes the rainfall increasing and the land surface temperature decreasing dramatically over the Qinghai-Xizang Plateau.

However, the basic structures of the general circulation have not changed fundamentally with the increasing elevation. When the Eastern Hemisphere orography is smooth, the southwesterlies in South Asia and the stronger deflective southerlies to the east of the Plateau are still existing. The circulation systems in the Northern Hemisphere have a two-wave zonal structure which is very agreeable with the two-wave zonal distribution of the land and the sea. It is proved that the land-sea distributive pattern is the decisive factor in forming the modern general circulation pattern under the fixed radiation forcing.

The studies of the geologic history proved that the Qinghai-Xizang Plateau truly uplifts step by step, grows out of nothing, from lower to higher. But it is imperfect to simulate the climatic status in the geologic age only according to the Qinghai-Xizang Plateau elevation during that period (other parameters fixed), and to compare it with the geologic observational data of the climatic changes in the Northern Hemisphere continents in the same geologic age. The cause is that, firstly, from the middle and late Cenozoic Era when the Qinghai-Xizang Plateau began to uplift, the underlying surface conditions, such as the land-sea distribution (due to the regression or the continent shift), the underlying surface albedos (especially in the Ice Age) and the sea surface temperature, have greatly changed besides the variations of the orographic heights; secondly, due to the changes of the earth orbital parameters, the solar radiation has also changed (the range of changes of the solar radiation reaching the top of the atmosphere exceeds 7 per cent between the present and 10 kaBP). All these factors would produce influences on the general circulation and climate changes, so the specific earth environments should be considered, especially the land-sea distributions during that period of time when the paleoclimate is to be simulated.

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