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NUMERICAL STUDY ON INFLUENCE OF QINGHAI-XIZANG (TIBETAN) PLATEAU ON SEASONAL TRANSITION OF GLOBAL ATMOSPHERIC CIRCULATION

ZHENG Qing-lin (郑庆林)[1] ZHANG Chao-lin (张朝林)[1] and LIANG Feng (梁 丰)[2]

(1.*Chinese Academy of Meteorological Science, Beijing* 100081 *China*; 2. *Beijing Institute of Meteorological Research, Beijing* 100031 *China*)

ABSTRACT: It is a worthwhile attempt to address the role of the Qinghai-Xizang Plateau in the seasonal transition of general circulation from a global prospective. In this paper, the CCM1 (R15L7) – LNWP spectral model is used to study the influences of the Qinghai-Xizang Plateau on the seasonal transfer of the general circulation, with the objective analysis form the State Meteorological Center for March 17, 1996 as the initial field. A mid-level heating source in regions on the same latitudes is shown to cause a warming center of 224 K to form on the level of 200 hPa that warms up the atmosphere by more than 7 K and a drop of temperature by about 6 K on most of the 200-hPa layer over the Antarctic continent, with the largest negative center being –8.28 K. It is favorable to the deepening and widening of the polar vortexes in the course of transition from summer to winter. The topographic effect of the plateau plays a vital role in forming and maintaining the mean troughs and ridges of the atmospheric circulation in Northern Hemisphere such that it strengthens (weakens) the south-north positive gradient of temperature on the northern (southern) side of the latitude zone in which the plateau sits and increases the north-south gradient of temperature near 30°N. The seasonal transition is thus favored so that the bulk travel of global westerly at the middle latitudes and the formation of Asian monsoon in early summer are made possible. In the equatorial and low-latitude areas where the geopotential is increased, the effect of the plateau terrain is also evident in that it is favorable for the northern withdrawal of the tropical high ridge in Southern Hemisphere and the northern shift of the subtropical high in Northern Hemisphere. In addition, the effect also helps increase the polar easterly over the Southern Hemisphere and weaken the low zone at 500 hPa. It acts as an increasing factor for the polar vortex around the Ross Sea and contributes to the genesis of the Somali Jet on the equator.

Key words: Qinghai-Xizang Plateau; seasonal transition; jet stream

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1 INTRODUCTION

Being the highest and most complex plateau in the world, the Qinghai-Xizang Plateau exerts important influence on the general circulation for Asia and the world due to its huge volume and special status in the westerly. Addressing from the observational and dynamic study, Ye, Tao and Li (1958) and Zhu (1957) discover and confirm many of the facts relating to the effects of the Qinghai-Xizang Plateau on abrupt seasonal changes in the general circulation, westerly jet branches, and formation of constant planetary systems. With the application of numerical modeling methods

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Biography: ZHENG Qin-lin (1939 –), male, native from Xianyou County Fujian Province, professor and advisor of Ph.D. candidates at Chinese Academy of Meteorological Sciences, majoring in atmospheric circulation and numerical prediction.

in areas of general circulation research, a series of experiments have been carried out in which the plateau effect is included as one of the important causes for its formation. As is shown in the study of Manabe and Terpstra (1974), the rainy belt going through the entire belt of middle latitude in the version without mountains is partitioned by less rainy belts over central Asia and middle North America in the version with mountains, because of the blockage of the Tibetan Plateau and Rocky Mountains. With an 11-layer GCM model, furthermore, Hohn and Manabe (1975) study the role of the Tibetan Plateau in the circulation of South Asian monsoon. It is shown that the modeling is relatively good of the northward jump of the subtropical westerly jet and the Southwest Monsoon with the plateau included in the model; when the plateau is removed, however, the jet just moves slowly towards north without any abrupt jumps with its location about 10 degrees of latitude south of where the westerly is observed. Using a 7-layer primitive equations spectral model, Zheng and Liou (1984) study the influence of dynamic and thermodynamic processes of the plateau on the general circulation, with the conclusion that better representation in the model of diabatic heating, radiation and cumulus convection is realized when the coupling dynamic and thermodynamic effects due to terrain are included. In their study of the influence of the plateau on precipitation during the onset period of summer monsoon in East Asia in 1979, Yan and Zheng (1991) use a T42L9 spectral model to study the influence of the Tibetan Plateau on precipitation during the 1979 outbreak of summer monsoon in East Asia. They point out that it is the thermodynamic force of the plateau in early summer that speeds up the northward jump of the southern branch of the westerly jet while net dynamic force greatly weakens it or even pushes it southward after the jump.

It is apparent that the work above either concentrates on simulating features of a particular season or focuses on medium-term synoptic processes associated with the plateau; in the study of the role of the plateau in the seasonal transition of the general circulation, the effect of East Asia monsoon is picked up as the main subject. In fact, the seasonal transition takes place on the scale of the global extent. Based on it the current work uses the CCM1 (R15L7) – LNWP model to simulate successfully the general circulation across the globe for May 1996 in order to study the role of global atmospheric circulation in the transition of flow pattern from winter to summer.

2 BRIEF ACCOUNT OF MODEL

The CCM1 (R15L7) –LNWP model used in this work has been developed on the basis of a NCAR's CCM1 (R15L12) model, which is successful in the application in long-term numerical prediction and numerical modeling of general circulation. Major changes and improvements include: 1) The model is changed from unequally-spaced 12 layers to equidistant 7 layers; 2) Corresponding fine modifications have been made to the vertical structure of clouds, radiation, convective adjustment and horizontal diffusion; 3) the initial values of the model change from fixed NCAR case data to arbitrary routine objective analysis ones; 4) the non-linear equilibrium equations are initialized to filter out the gravity inertia waves in the initial values; 5) the $p-s$ plane iterative interpolation is used to improve the accuracy of the initial values.

3 EXPERIMENT DESIGN AND VERIFICATION OF FORECASTS

3.1 *Experiment design*

The current work chooses the National Meteorological Center's global objective analysis data for March 17, 1996. The initial values have been treated to adopt to specific requirements of the model. In a 75-day long-term numerical prediction experiment, attempts have been made to determine how the Qinghai-Xizang (Tibetan) Plateau affects the global general circulation. The work is done with the following schemes of:

(A) a control experiment, in which a full set of physical processes is included in the model and

(B) an experiment without the plateau, in which the terrain has been lowered to the altitude of 500 m for the plateau region in the control.

For the experiments above, the initial values of individual elements on the σ plane are obtained through interpolation of values on the *p* plane by the method of iteration. The treatment is motivated by the advantage that error so arisen is small enough to treat the difference at the initial time between the two experiments as zero. With 75 days of integration, the forecasts of both experiments return from the σ plane back to the *p* plane before output. The difference now is whether the plateau (in terms of both dynamic and diabatic heating) has been included in the handling concerning its terrain effect on the general circulation.

3.2 *Verification of experiment results*

Tab.1 gives the results of verification of Experiment A (Exp.A) against the monthly mean geopotential fields at 500 hPa within the Northern Hemisphere. It is known from the table that Exp.A is capable of making good long-term forecasts and for all of the four regions listed the monthly anomalous correlation coefficient is all above 50% and the root-mean-square error is all below 5 geopotential meters (gpm). Region 3 has the best result, with the *t* value acquiring 69% and ε 3.8 gpm. Other regions also have simulations that forecast realistic distribution of troughs and ridges and location and intensity of highs and lows. Corresponding verification is also conducted for Exp.B, which shows a less satisfactory result as compared to Exp.A with *r* being 40% and ε 4.2 gpm for the Asian region (Reg.4). All of the verifications suggest that the studies to carry out in this paper — sensitivity experiments and comparisons between them — are significant in investigating the role of plateau terrain in affecting the global circulation.

Tab. 1 Correlation coefficient *r* and R.M.S. error for monthly anomalies for 500-hPa geopotential field in Exp.A

	Reg.1	Reg.2	Reg.3	Reg.4
r / %	50	67	69	53
e / gpm	49	48	38	32

Note: Reg.1: Northern Hemisphere; Reg.2: 0~ 87.5°N, 0~180°E; Reg.3: 0~ 87.5°N, 90°E ~180°E; Reg.4: 17.5°N ~ 60°N, 60°E ~140°E

4 RESULTS OF NUMERICAL EXPERIMENTS AND DISCUSSION

4.1 *Influence on temperature fields*

Fig.1 gives the monthly mean 500-hPa temperature fields and deviations for May 1996 as predicted by Exp.A and Exp.B. From the comparison, it is not hard to find that the warm zone, which is predicted by Exp.A to center around the region of the Tibetan Plateau and cover the vast areas from the Arabian Peninsula to the Philippines, has disappeared on the map for Exp.B. It is then suggested that the heating effect of the plateau in early summer on the low-latitude atmosphere be closely related with the massive terrain. The region could not have been the center of heating for areas of the same latitudes if there had not been the terrain, which is an indirect

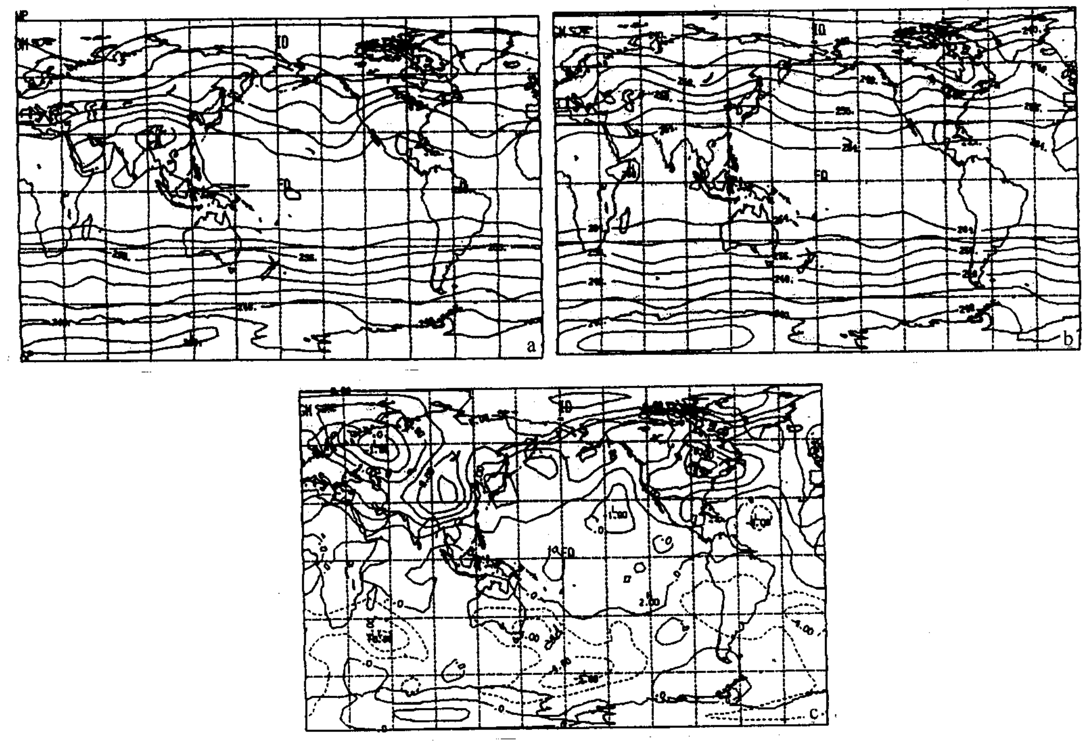

Fig.1 Monthly mean temperature field at 500 hPa in May 1996 (unit: K). (a) predicted field of Exp.A; (b) predicted field of Exp.B; (c) distribution of difference between Exps.A and B

indication that the plateau heating in May takes place mainly in the form of sensible mechanism. For the distribution map of difference which is obtained by subtracting Exp.B from Exp.A (Fig.1c), there is a large positive zone over the Tibetan Plateau and low-latitude areas south of it with the positive center being as high as 10.9 K while a negative zone appears through the Ural Mountains with a –1.59 K center. The distribution accounts for the positive role of the dynamic and diabatic effects arisen from the plateau terrain in the increase (decrease) of the north-south positive temperature gradient north (south) of the plateau. There is also a zone of positive difference over the North America continent of the same latitudes (the center being 0.5 K), which blocks cold air mass coming from higher latitudes and favors the northward seasonal shift of the northern westerly. With the plateau removed, moreover, some changes have taken place in the temperature field of the Southern Hemisphere — temperature goes up sharply over the oceanic region in the middle latitudes and the cold vortex increases over the eastern part of the Antarctica.

Examining the monthly 200-hPa mean temperature figure (omitted) for Exp.A, we know that there is a 224-K closed warm center over the plateau, a sign that the heating of atmosphere by the plateau in early summer is extended all the way to the tropopause. The highest absolute temperature of the northern middle latitude at 200 hPa is found not right over the plateau, as in the case of the 500-hPa layer, but over Turkey and areas northeast of the Mediterranean. However, the plateau still plays an important role in the heating up of the atmosphere on the 200-hPa layer, as indicated in the difference map that the positive centers are largely of the same intensity at 7.48 K and 7.93 K relatively over the plateau and the region of Turkey. With the removal of the plateau, the heating over the entire Asian and African continents becomes much weaker and the vast Pacific warm zone that is from North America to eastern Australia has shrunk to areas over the northern subtropical eastern Pacific while the temperature rises south of 30°S. The difference map (omitted) shows that temperature falls on the 200-hPa layer for most of the Antarctic continent due to the plateau effect, being favorable for the deepening of intensity and increase of coverage of the vortex around the pole in transition from summer to winter in the Southern Hemisphere. In the meantime, a large zone of positive values forms over the low latitudes in the hemisphere as a result of the plateau terrain – such positive-north- and negative-south distribution of the difference increases the gradient of positive temperature from north to south around 30°S and favors the seasonal northward travel of the subtropical high ridge and westerly jet in the Southern Hemisphere.

4.2 *Influence on temperature fields*

Like the temperature field, the topography of the plateau also poses great influence on the field of geopotential height. At the layer of 500 hPa, the low trough that is originally active between the Newland Island and Lake Balkhash has turned into a region of ridges with a closed low appearing north of the Lake Bajkal. The bifurcation of westerly by-passing the plateau has disappeared, the trough region much weakened east of the Kamchatka Peninsula and the subtropical high belt decreased. In summary, disturbances in the northern westerly will be much weaker, the contours smoother and longwave disturbances reduced in the middle latitude of the Southern Hemisphere if the Tibetan Plateau is removed.

As shown in the difference maps of monthly mean geopotential height for 500 hPa (Fig.2a)

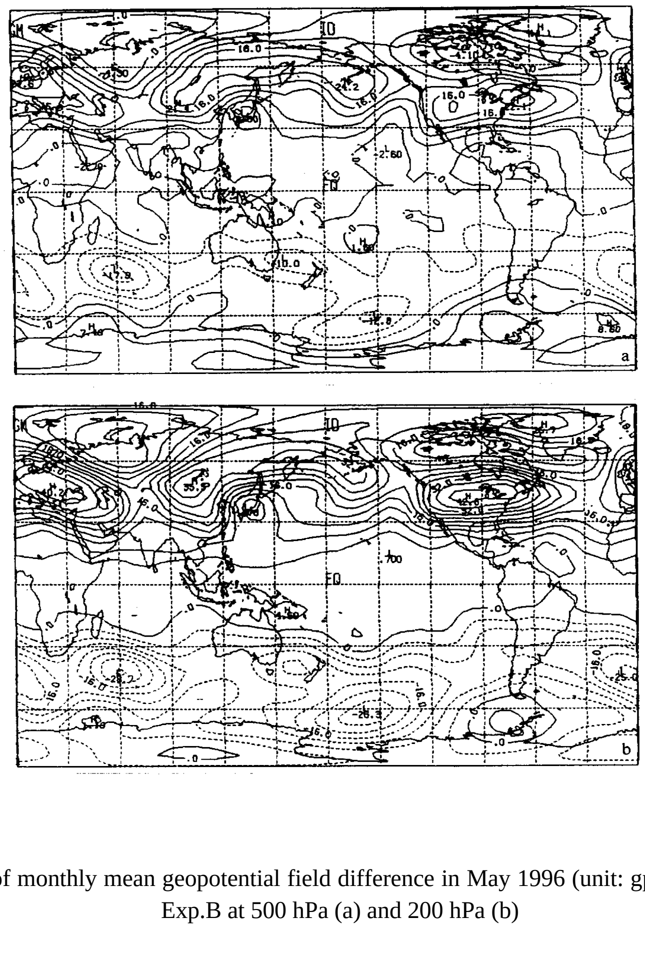

Fig.2 Distribution of monthly mean geopotential field difference in May 1996 (unit: gpm) between Exp.A and Exp.B at 500 hPa (a) and 200 hPa (b)

and 200 hPa (Fig.2b), available by subtracting Exp.A from Exp.B, we find a basically consistent distribution of difference — there are two strong centers of low pressure in the Northern Hemisphere, locating relatively over the Ural Mountains and northeastern North America. They are corresponding to two longwave troughs on the mean map while the positive zone that separates the two negative centers is corresponding to the ridge region. It is a suggestion that the forcing effect of the plateau is playing an essential role in forming and maintaining the mean troughs and ridges in the Northern Hemisphere. The map of difference also indicates that a belt of strong negative difference prevails in the middle latitudes of the Southern Hemisphere, which is flanked by weak negative or even positive zones in lower and higher latitudes. It attributes to a situation in which the geopotential height fields increase or maintain in the high and low latitudes but decrease in the middle latitudes, being favorable for the northward retreat of the subtropical high zone. The plateau terrain, however, causes the polar low-pressure zone to weaken on the 500-hPa layer but strengthen slightly on the 200-hPa layer, in the Southern Hemisphere. On the other hand, there is obvious intensification on both layers for the low center around the Ross Sea. In addition, a weak negative zone is found to the southeast of the Tibetan Plateau corresponding to the lowered geopotential height, as indicated in the 500-hPa difference map. It is jointly caused by the bifurcation of the westerly by the plateau and lee side effect. The plateau terrain is such on the 200-hPa layer that the dynamic role has fallen sharply and diabatic heating has grown to become a principle factor. It is then not a surprise to find that there is an increase of geopotential height over the Tibetan Plateau and areas adjacent to it.

4.3 *Influence on convection fields*

4.3.1 HORIZONTAL FLOW FIELDS

From the figure (omitted) of the 500-hPa flow field in Exp.A, we know that the mid-latitude westerly turns into two branches, strong in the north and weak in the south, to the west of the Tibetan Plateau, with a zone of weak winds right over the plateau. After the by-passing, the westerly rejoins over eastern China and becomes stronger to form a jet stream over Japan. In the high latitudes, a northwesterly flow flowing from the Iceland to the Eurasian continent is blocked by the northern branch of the westerly jet and turns north of the Tianshan Mountains into a southwest flow that travels back to the pole. A simpler pattern of flow is found for the Southern Hemisphere. Its wave forcing is mild with largely a smooth westerly in action over the middle latitudes, though with wind speed greater than the other hemisphere. The axis of the jet stream is near 30°S. There is a strong cyclonic circulation over the region of the Ross Sea corresponding to the polar vortex. The cross-equatorial Somali Jet, which forms near 45°E, suggests the onset of transition of the general circulation. With the plateau removed, however, the westerly no longer splits into two, the strong pattern of two ridges plus one trough is replaced by a smooth westerly over the northern Pacific and the cyclonic circulation that forms on the eastern coast of the continent after the passage of the Rocky Mountains is also weakened. Consequently, the Somali Jet almost vanishes, the axis of the Southern Hemisphere westerly jet is moved southward to around 45°S to decrease the intensity of the polar vortex.

The plateau topography influences the 200-hPa-flow field in much the same way as it does with the 500 hPa one. The difference is that there is an intense anti-cyclonic circulation on the 200-hPa level (Fig.3a), which is caused by terrain-associated diabatic heating. Because of a mid-level heating source made available by such massive plateau terrain for areas of the same latitudes, the longitudinal distribution of temperature is altered over regions surrounding it so that the anti-cyclonic nature is increased as deducted from the relation of thermal wind, considering in addition

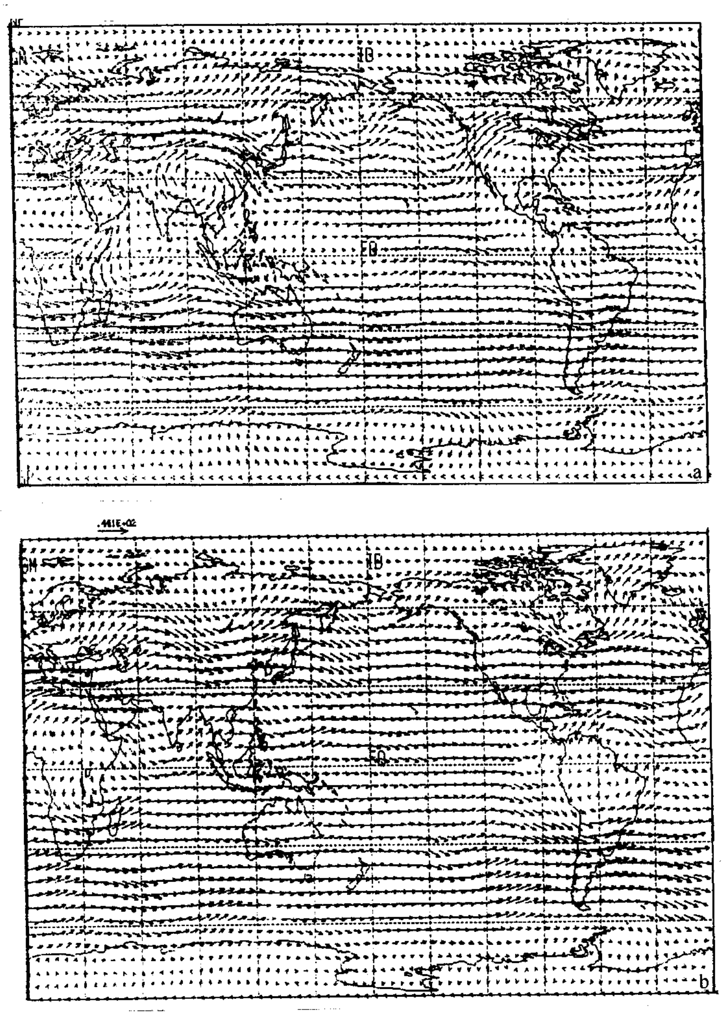

Fig.3 Monthly mean flow field at 200 hPa in May 1996. (a) Exp.A; (b) Exp.B

the weak dynamic by-passing effect at 200 hPa over the plateau. Another point to note is that between 30°E and 60°E there is an obvious air current crossing the equator from the Northern Hemisphere which meets the westerly near 15°S (Fig.3a). Consequently, air mass piles up and sinks by some degree, being favorable for the genesis of the Somali Jet at the low levels. In contrast, the same cross-equatorial current is much weakened at 200 hPa, which is clear in Fig.3b that represents the plateau.

4.3.2 ZONAL FLOW FIELDS

On the vertical cross-section (Fig.4a) of zonal wind averaged over the parallel, there is a westerly 200-hPa maximum each in the Southern and Northern Hemisphere over the middle latitudes. One of the maxima is found around 45°N for the latter hemisphere while weak easterly prevails over the equator, lower latitudes and tropopause in conjunction with a westerly zone in mid-troposphere. An easterly zone dominates the Antarctic continent from surface to upper levels, leaving layers near the surface in the Arctic region in the control of an easterly wind. From the difference map (Fig.4b) obtained by subtracting Exp.A from Exp.B, one can infer the effects of

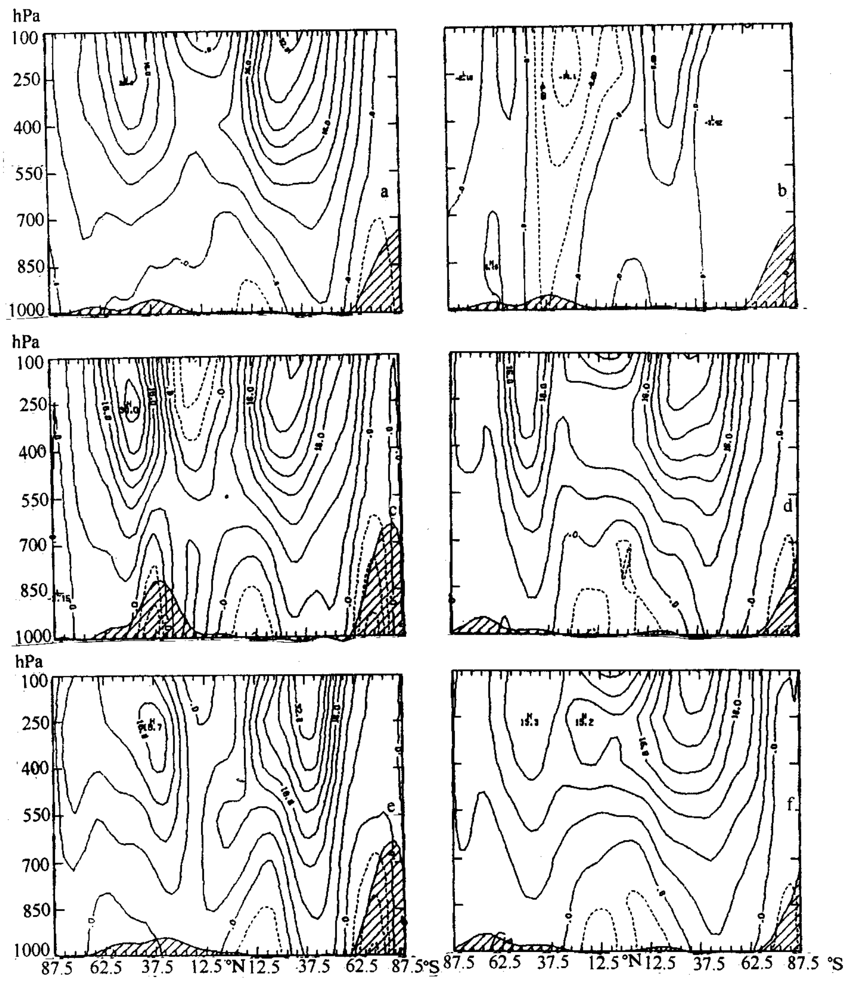

Fig.4 Vertical profile of monthly mean zonal wind in May 1996 (unit: m/s). (a) vertical profile of zonal wind averaged over latitude circle in Exp.A; (b) same as (a) but for the difference between Exp.A and Exp.B; (c) zonal wind averaged over 40°E ~ 120°E in Exp.A; (d) same as (c) but for Exp.B; (e) zonal wind averaged over 150°W ~ 15°W in Exp.A; (f) same as (e) but for Exp.B

plateau terrain on the zonal wind. (1) The entire region from 22.5°N to 47.5°N is of negative difference against a positive one north of it, corresponding to zones of westerly weakening and strengthening respectively. It suggests that the dynamic and diabatic heating effects due to the plateau terrain in early summer have caused the strengthening of the northern and the weakening of the southern zone of the westerly in which it is situated. In other words, the plateau accelerates the seasonal shift towards north of the whole westerly zone in the Northern Hemisphere. (2) The middle and low latitudes in the Southern Hemisphere are covered with vast areas of positive values with the positive center near 30°S and the intensity as high as 8 m/s against weak negative zones all to the south of 40°S. It is an indication that the plateau terrain is favorable for the northward travel of the middle-latitude westerly and the strengthening of the polar easterly in the Southern Hemisphere.

Because of the specific reflection of zonal circulation on different longitudes, vertical cross-sections are compared and illustrated for the Eurasian and North American regions to have a clearer picture of the influence of the plateau on atmospheric circulation in different regions.

Figs.4c ~ 4f give the vertical profiles of zonal wind in Exps.A and B, in which Fig.4c and Fig.4d are the mean over 40°E ~ 120°E, representing the region of Eurasian continent and Fig.4e and Fig.4f are the mean over 150°W ~ 15°W, representing North America. Examining Fig.4c and Fig.4e in comparison, we find that the jet centers are relatively 30 m/s and 32 m/s in the subtropical westerly in the Eurasian continent and corresponding area in the Southern Hemisphere. They are all stronger than in the relevant regions in North America. So do the easterly winds in both poles. In Fig.4c, the close-to-surface equatorial easterly is weak, covers smaller domain and leans towards the Southern Hemisphere while the corresponding region in Fig.4e is of wide tropical easterly zone. In addition, in the subtropical region between 40°E and 120°E, there is an easterly on 400 hPa with a central speed of 8 m/s, a phenomenon absent in Fig.4e.

With the removal of the plateau (Figs.4d and 4f), the westerly jet axises in both regions of the Northern Hemisphere all move to 35°N, with the central intensity decreasing from 30 m/s to 25 m/s for the Eurasian region but increasing from 20 m/s to 24 m/s for North Africa. For the former region, the tropical easterly expands with weakened intensity; for the latter, it does not have much change with the location somewhat more southward. The westerly jet weakens in both regions in the Southern Hemisphere and with the decreasing of upper-level westerly, lower-level easterly regains some of the intensity in higher latitudes.

4.3.3 MERIDIONAL FLOW FIELDS

Fig.5 is the vertical cross-section of V field averaged over 40°E ~ 120°E. With the presence of

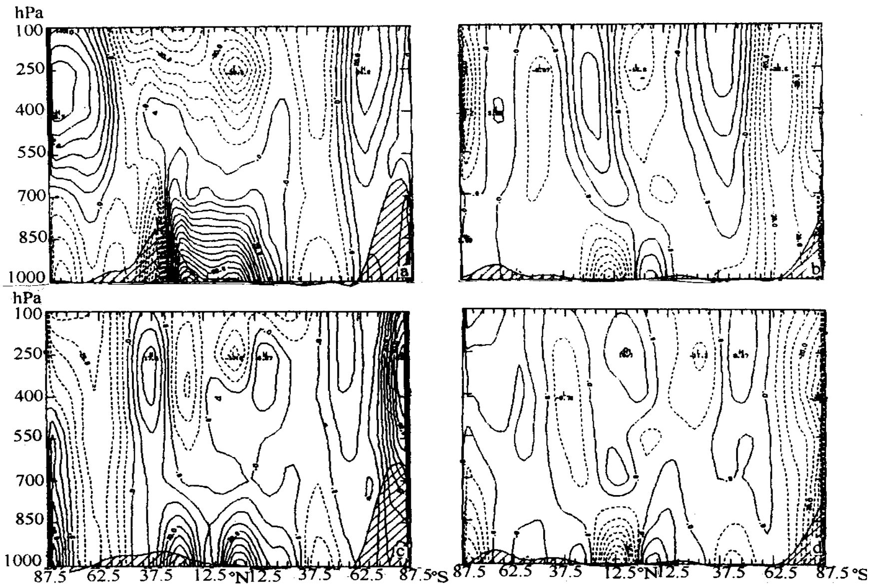

Fig.5 Vertical profile of monthly mean V field (unit: 0.1 m/s). (a) vertical profile of V field averaged over 40°E ~ 120 °E in Exp.A; (b) same as (a) but for Exp.B; (c) vertical profile of V field averaged over 150°W ~ 15°W in Exp.A; (d) same as (c) but for Exp.B

the plateau (Fig.5a), south and north winds converge over the southern plateau and upper-level divergent flows cross the equator and sink in low-latitude areas of the Southern Hemisphere. With the plateau removed (Fig.5b), the southerly takes control in layers under 700 hPa from 35°S to 47.5°N. Air flows rise over the equator and subtropics and sink at the meeting line of the southerly and northerly at 47.5°N, maintaining to a large extent the winter pattern of the Hadley cell. In addition, the polar southerly of the Southern Hemisphere and high-latitude northerly of the Northern Hemisphere also get much strengthened when the plateau is excluded.

5 CONCLUDING REMARKS

a. The heating of the atmosphere in early northern summer by the Qinghai-Xizang Plateau is closely associated with its massive terrain. Being a middle-level heating source for areas with the same latitudes, the plateau acts to form a closed warm center of 224 K at 200 hPa, warming the atmosphere by more than 7 K.

b. The dynamic and diabatic heating induced by the terrain of the plateau is found to play a vital role in the formation and maintenance of mean troughs and ridges in the general circulation of the Northern Hemisphere. Disturbances will be much reduced in the westerly of the middle latitudes of the Northern Hemisphere if the plateau is removed.

c. In May, the orographic effect of the plateau is such that the south-north positive gradient of temperature is increased (decreased) to the north (south) of the latitude zone where the plateau is situated. In the meantime, the north-south positive gradient of temperature near 30°S is also strengthened so that the axis of the westerly jet stream in the middle latitudes of the Southern Hemisphere is forced to go back to around 30°S from 45°S, being favorable for the seasonal transition of global atmospheric circulation.

d. The areas of geopotential increase formed as a consequence of the plateau's terrain effect in the equator and low latitudes are favorable for the northward retreat of the southern subtropical high ridge and the strengthening and northward shift of the northern subtropical high, contributing essentially to the formation of the circulation cells of the summer monsoon in Asia.

e. The plateau terrain is playing a significant role in the deepening of intensity and the expansion of domain concerning the polar vortexes during the transition from summer to winter. In addition, it also exerts great influence on the formation of the Somali jet that crosses the equator.

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