Thermal adaptation of the large-scale circulation to the summer heating over the Tibetan Plateau*

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Abstract The potential vorticity equation is employed to diagnose the variation in the large-scale atmospheric circulation in July by using the NCAR/NCEP daily reanalysis data from 1986 to 1995. Based on the theory of thermal adaptation, the schematic diagram of the formation and maintenance of the circulation over the Tibetan Plateau is revealed in this paper. The result shows that near the surface of ground is the positive potential vorticity source produced by the increasing diabatic heating with height, which maintains the cyclonic circulation, and that the positive Ertel potential vorticity (PV) source is balanced by friction dissipation. On the other hand, in the upper troposphere the negative PV produced by the decreasing diabatic heating with height maintains the anticyclone, and it is balanced by the divergence of the negative PV. The Gauss' theorem has been applied to analyze the Ertel potential vorticity flux crossing each of the lateral boundaries of the area over the Tibetan Plateau. The result shows that the negative PV flux is transferred through the eastern and northern boundaries of the area from the Tibetan Plateau region to the outer world. It is evident that the Tibetan Plateau region is an important source of negative vorticity of the atmosphere.

Keywords: Tibetan Plateau, potential vorticity, diabatic heating, thermal adaptation.

It is well known that the air-column over the Plateau is intensely warmed in summer, and there is an obvious cyclone in the lower layer and there is a deep anticyclone in the upper layer of the atmosphere over the Tibetan Plateau[1~5]. The mechanism linking the diabatic heating of the Tibetan Plateau to the large-scale circulation has received continued attention for a long time[6~9].

In this study, the transformed Ertel potential vorticity equation is employed to analyze the budget of PV using the NCAR/NCEP reanalysis data sets obtained at the Institute of Atmospheric Physics, Beijing (IAP) Data Center, then the thermal adaptation theory is applied to analyze the impacts of the diabatic heating over the Tibetan Plateau on the large-scale circulation.

1 Features of the circulation and diabatic heating over the Tibetan Plateau in summer

Over the Tibetan Plateau in summer, there exists a persistent cyclonic circulation in the lower layer with positive vorticity and convergence, and there exists a deep anticyclonic circulation in the upper layer with negative vorticity and divergence.

Such features of circulation and vorticity in the vertical direction are related to the profile of the

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diabatic heating. Fig. 1 shows the vertical profiles of the July mean diabatic heating for the period 1986 ~ 1995 over the Tibetan Plateau and the Bay of Bengal. All data of the heating rate are obtained from the NCAR/NCEP reanalysis data sets. Its horizontal resolution is 1.875° × 1.875°. There are 28 σ-layers in the vertical direction, ranging from 0.995 to 0.027. The domain of the Tibetan Plateau for the calculation is 80°E ~ 100°E and 27.5°N ~ 37.5°N. The maximum (over 10 K/day) of the diabatic heating over the Tibetan Plateau occurs in the lower layer near the ground, indicating that the fundamental contribution to the total diabatic heating in the lower layer is due to the *in situ* sensible heating (that has its maximum of 11 K/day at the lowest level). In contrast, for the profile of the diabatic heating over the Bay of Bengal (averaged over 80°E ~ 100°E and 10°N ~ 20°N), the maximum occurs around the height of 300hPa, which is coincident with the profile of the condensation heating rate. Evidently, over the Bay of Bengal the condensation heating makes the main contribution to the *in situ* heating. The difference in the vertical profile of heating means that the circulation over the Tibetan Plateau is of features guite different from those over the Bay of Bengal.

Figure 2(a) shows the longitude-height section along 30°N of the July potential temperature and

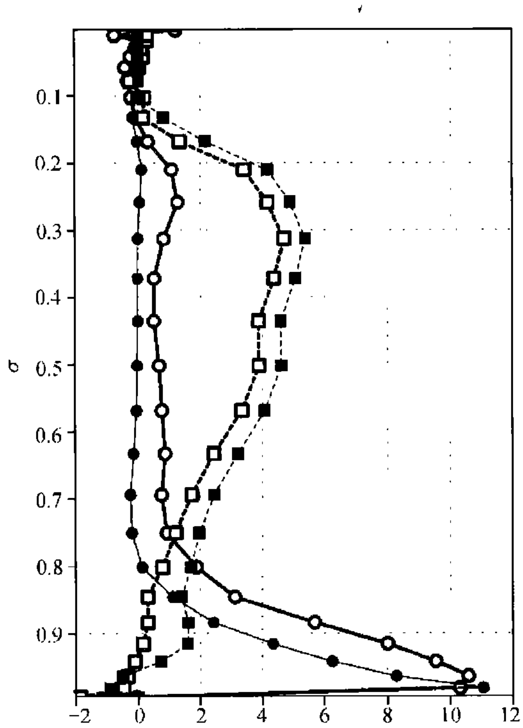

Fig. 1 Vertical profiles of the July mean (1986—1995) diabatic heating over the Tibetan Plateau and the Bay of Bengal. Unit is K/day. ○ and ● stand for the total and vertical diffusion diabatic heating rate over the Tibetan Plateau respectively, and □ and ■ stand for the total and condensation heating rate over the Bay of Bengal respectively.

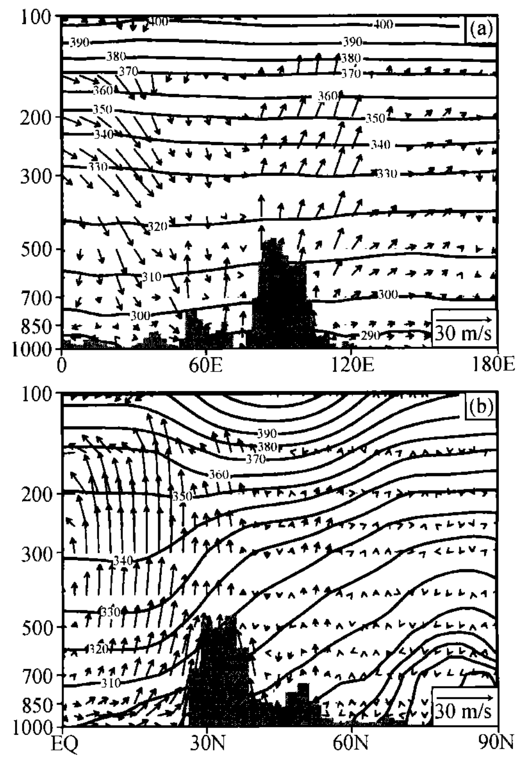

Fig. 2 Height-longitude cross-section of the July means (1986 ~ 1995) potential temperature in contour and the vertical circulation in vector. The interval of isotherm is 10 K; (a) Along 30°N; (b) along 90°E.

wind averaged between 1986 and 1995. This latitude passes through the Tibetan Plateau. During summer there is a relatively warm center of potential temperature and the strong ascent prevails over the Tibetan Plateau and the area of the East Asian monsoon (the vertical velocity is multiplied by 10^3). Similar result is also obtained from the latitude-height section along 90°E (Fig. 2(b)): the potential temperature over the Tibetan Plateau is higher than that over other areas, and there is a strong ascent velocity associated with those over the Bay of Bengal. The above discussion shows that the regions from the Plateau to the area of the East Asian monsoon, and from the southern flanks of the Plateau to the area of the Bay of Bengal are important heat source regions of the atmosphere in summer.

2 Ertel potential vorticity and its budget

The transformed Ertel potential vorticity equation is given by[10]

$$\frac{\mathrm{D}W}{\mathrm{D}t} = \boldsymbol{\zeta}_a \cdot \nabla\dot{\theta} + \boldsymbol{F}_\zeta \cdot \nabla\theta, \tag{1}$$

where θ is the potential temperature, $\dot{\theta} = \frac{\mathrm{d}\theta}{\mathrm{d}t}$ the diabatic heating rate, $\boldsymbol{\zeta}_a$ the three dimensional absolute vorticity vector, $\boldsymbol{F}_\zeta$ the friction dissipation, and the volume potential vorticity $W = \boldsymbol{\zeta}_a \cdot \nabla\theta$. The transformed differential operator $\frac{\mathrm{D}}{\mathrm{D}t} = \frac{\partial}{\partial t} + \nabla \cdot \boldsymbol{V}$.

The term on the left-hand side of Eq.(1) indicates the variation in the potential vorticity, and the terms on the right side of it suggests the contributions to the PV variation coming from the diabatic heating and friction dissipation, respectively. For monthly mean, the local variation is small and can be omitted. Using an overbar to denote the monthly mean, and a prime to denote the deviation from it, we can rewrite Eq.(1) as

$$\nabla \cdot \overline{\boldsymbol{V}}\overline{W} = \overline{\boldsymbol{\zeta}_a} \cdot \nabla \overline{\dot{\theta}} + R, \tag{2}$$

where

$$R = \boldsymbol{F}_\zeta \cdot \nabla\theta + \overline{\boldsymbol{\zeta}'_a \cdot \nabla \dot{\theta}'} - \overline{\nabla \cdot \boldsymbol{V}'W'} \tag{3}$$

is the residual term of Eq.(2), representing the effects of frictional dissipation and the transient processes with a time scale less than 12 h. Using 12 h (00Z and 12Z) NCEP/NCAR reanalysis data for July from 1986 to 1995, the major terms of Eq.(2) are calculated. The diabatic heating rate ($\dot{\theta} = \frac{\mathrm{d}\theta}{\mathrm{d}t}$) is inversely computed from the distribution of θ. For the purpose of reasonably processing the complex orography and the feature of the near-surface maximum diabatic heating over the Tibetan Plateau, the σ coordinate system is used in the computing. We conceptually choose $\sigma = 0.4357$ and $\sigma = 0.995$ layers to represent the high and low layers of the atmosphere. The former is near 250 hPa and the latter is near ground over the Tibetan Plateau.

The PV budget at $\sigma = 0.4357$ is shown in Fig. 3(a, b). The distribution of the divergence of the potential vorticity flux (Fig. 3(a)) exhibits two strong negative centers, with intensity of more than $2\times10^{-6}TUs^{-1}(1TU=10^{-6}Ks^{-1}\cdot m^{-1})$, on the eastern and north-western parts of the Tibetan Plateau, respectively. They are in good agreement with the distribution of the negative potential vorticity generation due to diabatic heating (Fig. 3(b)). Thus we can see that the effects of the frictional dissipation and the transient are small, and that the source of the negative vorticity in maintaining the anticyclone in the upper layer of the atmosphere over the Tibetan Plateau comes from a decrease in the diabatic heating with height.

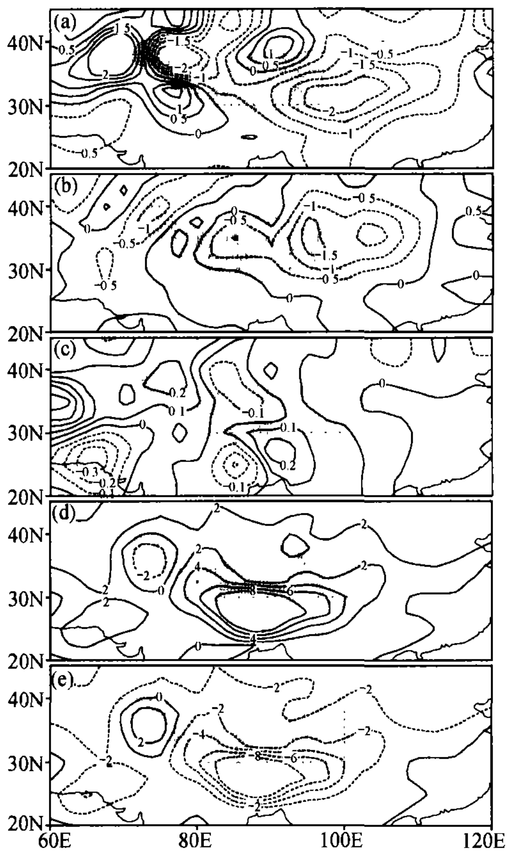

Fig. 3 Distribution of the July mean (1986 ~ 1995) items of the PV equation on $\sigma=0.4357$ level ((a) and (b)) and $\sigma=0.995$ level ((c), (d) and (e)). Regions over 3000 meters above sea level are shaded. (a) and (c) are the divergence of the PV flux; (b) and (d) are PV generated due to the diabatic heating; (e) the residual term R. Unit is $10^{-12}K\cdot m^{-1}\cdot s^{-2}$.

The result obtained here looks different from that of the Ref. [7]. In the latter, the classical vorticity equation is employed to diagnose the balance of vorticity, and the conclusion is that in July over the Tibetan Plateau the divergence of the vorticity flux is balanced by the contribution of the sub-grid-scale processes and the residual term (see Fig. 1 in Ref. [7]). Since there is no diabatic heating in the classical vorticity equation, it is hard to compare our result with theirs. However in Ref. [7] the contribution of the sub-grid-scale processes mainly referred to convective activity, a substantial part of the diabatic heating over the Tibetan Plateau in July. From this viewpoint, the inference of their research, although in an indirect sense, is consistent with the result of this study.

The PV budget at the $\sigma=0.995$ level is shown in Fig. 3(c ~ e). The strong center of the positive potential vorticity is on the southern side of the Tibetan Plateau from 25° N to 31° N (Fig. 3(d)), which reveals the importance of the near surface heating in the maintenance of the cyclone in the lower layer over the Tibetan Plateau. On the other hand, the divergence of VW (Fig. 3(c)) is too small to balance the positive potential vorticity generation due to the increase in the diabatic heating with height, the heating term is then mainly balanced by the friction and transient processes (Figure. 3(e)).

To analyze the vertical distribution of the budget of potential vorticity, profiles of the terms of Eq.(2) are computed at each grid point and averaged over the area of the Tibetan Plateau. The results are given in Fig. 4. The two curves (Fig. 4(a)) that represent the divergence of VW and PV generation due to the diabatic heating basically have the same trend above the boundary layer, implying that the two terms are generally balanced with each other in the upper layers over the Tibetan Plateau. However in the lower layer, the positive vorticity generation due to the diabatic heating is balanced mainly by the residual term (Fig. 4(b)). Based on the earlier and present results, we may conclude that the negative vorticity and divergence in the upper layers, and the positive vorticity and convergence in the lower layers over the Tibetan Plateau are mainly caused by the vertically inhomogeneous distribution of diabatic heating. The negative vorticity generation due to friction and the transient processes in the boundary layer is very important in offsetting the cyclonic circulation in the lower layer over the Tibetan Plateau.

3 Potential vorticity flux across the lateral boundary

To analyze the transfer of the potential vorticity at the lateral boundary of the air-column over the Tibetan Plateau, the PV fluxes crossing all lateral boundaries are calculated at each of the σ levels. Based on the Gauss law, the total divergence of the PV flux integrated over a volume V can be written as

$$TL = \iiint_V \nabla \cdot (\boldsymbol{V}W)\mathrm{d}V = \iint_{SW} \boldsymbol{V}W \cdot \boldsymbol{n}\mathrm{d}S + \iint_{SE} \boldsymbol{V}W \cdot \boldsymbol{n}\mathrm{d}S + \iint_{SN} \boldsymbol{V}W \cdot \boldsymbol{n}\mathrm{d}S + \iint_{SS} \boldsymbol{V}W \cdot \boldsymbol{n}\mathrm{d}S + \iint_{SU} \boldsymbol{V}W \cdot \boldsymbol{n}\mathrm{d}S + \iint_{SB} \boldsymbol{V}W \cdot \boldsymbol{n}\mathrm{d}S. \tag{4}$$

Let SW, SE, SN, SS, SU and SB denote the sum of the potential vorticity fluxes crossing respectively the western, eastern, northern, southern, upper and bottom boundaries. The sum of the 4 vertical boundaries is expressed for convenience as $\sum_4 = SW + SE + SN + SS$. So Eq.(4) can be simplified into

$$TL = \sum_4 + SU + SL = \sum_6 . \tag{5}$$

Figure 5 shows the PV transportation crossing each of the boundaries of the air-column over the Tibetan Plateau. The thickness of the σ layer, $\delta\sigma$, is equal to the difference between the two adjacent σ values in the NCEP/NCAR reanalysis data sets. Fig. 5(a) shows that the two curves TL and $\sum_6$ are very close to each other, indicating a satisfactory precision in calculating Eq.(4) by using the data. The profile of $\sum_4$ is negative in the whole column, suggesting that the atmosphere over the Tibetan Plateau is a negative vorticity source and transfers the negative PV to the surrounding area. The area integration of the PV fluxes crossing the upper and bottom boundaries is larger than the fluxes crossing the lateral boundary. This is because the horizontal scale of the calculation domain is much larger than its vertical scale; thus the area of its upper and bottom boundaries is much larger than its lateral boundary in the calculation. For a unit volume of the air parcel, however, the horizontal transportation of PV is much larger than its vertical counterpart.

Figure 5(a) indicates that the ascent motion transfers the positive PV crossing the upper boundary of a lower region over the Tibetan Plateau to the above region. It means that the positive PV produced by the diabatic heating in the lower layer is always transported to the upper layer over the Tibetan Plateau by an ascending flow.

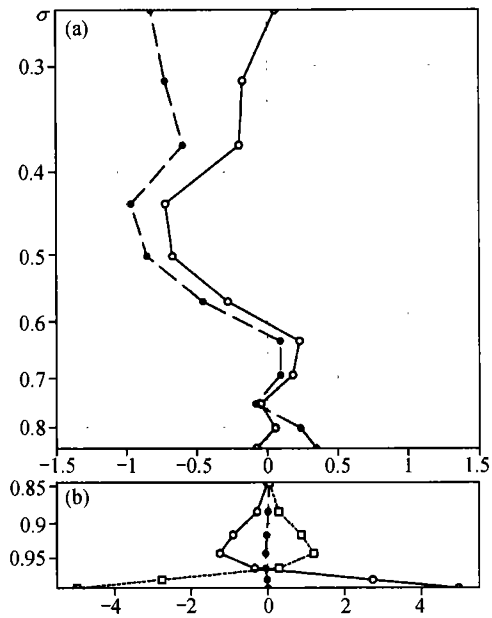

Fig. 4 Vertical profiles of the 10a (1986 ~ 1995) July mean the divergence of the PV flux (long dashed line), the PV generated due to the diabatic heating (solid line) and the frictional and transient term R (short dashed line) in the PV equation, which are averaged over the Tibetan Plateau for layers above $\sigma = 0.85$ (a), unit is $10^{-12}\ \mathrm{K \cdot m^{-1} \cdot s^{-2}}$; below $\sigma = 0.85$ (b), unit is $10^{-11}\ \mathrm{K \cdot m^{-1} \cdot s^{-2}}$.

Figure 5(b) shows the vertical profiles of the PV transportation crossing the 4 lateral boundaries over the Tibetan Plateau. The outward transportation of the PV crossing the western boundary is positive. At the southern boundary, the negative PV in the lower layer and the positive PV in the upper layer are transferred outward. On the other hand, at the northern and eastern boundaries, it is the negative PV that is transferred from the Tibetan Plateau towards outer regions. To investigate the net PV transfer in the zonal and meridional directions, the PV flux crossing the west and east boundaries, and crossing the north and south boundaries are separately added together, and the results are presented in Fig. 5(c). It shows that the negative PV flux crossing the eastern and northern boundaries are, respectively, larger than the positive PV flux crossing the western and southern boundaries except in the lower layers near the ground. In other words, the air-column over the Tibetan Plateau is a negative vorticity source in summer. The negative potential vorticity generated over the Tibetan Plateau due to the diabatic heating is transferred outward, crossing its lateral boundary towards its surrounding area.

4 Thermal adaptation of the atmospheric circulation to the diabatic heating over the Tibetan Plateau

The theory of thermal adaptation[10] and the results obtained from the above analysis can be used to investigate the impacts of the diabatic heating over the Tibetan Plateau on the formation and maintenance of the large-scale circulation. Both scale analysis[9] and data diagnosis (figures omitted) indicate that the PV generation due to the inhomogeneous diabatic heating in the vertical direction is much stronger than that by the inhomogeneous diabatic heating in the horizontal direction. Over the Tibetan Plateau, the maximum heating layer is near the ground surface and the absolute vorticity is positive; thus in a shallow layer below the maximum heating $(f + \zeta_z)\dfrac{\partial \dot{\theta}}{\partial z} > 0$, a positive PV is produced. The profile of the diabatic heating over the Tibetan Plateau (Fig. 1) shows that the vertical gradient of heating rate is large below the maximum heating layer, hence the positive PV produced by the diabatic heating is very large in the lower layer. But in the deep space above the maximum heating layer the vertical gradient of heating rate is negative, $(f + \zeta_z)\dfrac{\partial \dot{\theta}}{\partial z} < 0$; thus the negative PV is produced in the deep space above the maximum heating layer over the Tibetan Plateau.

The cross section of the potential temperature and the wind vector in July (Fig. 2) shows that over the Tibetan Plateau the strong diabatic heating leads to the permanent downward extension of the

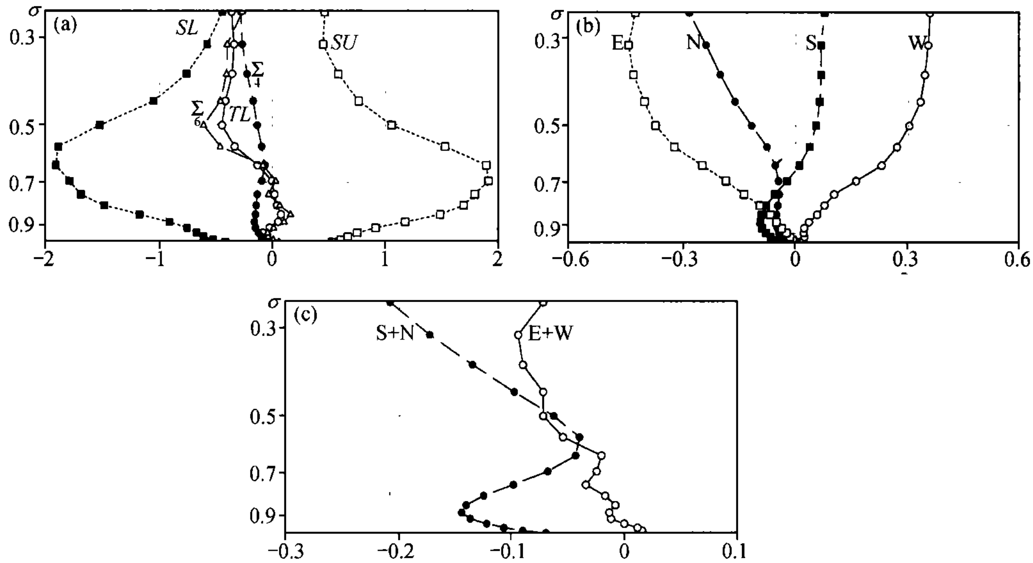

Fig. 5 Integration profiles of the July mean (1986 ~ 1995), the divergence of the PV flux and the PV flux crossing lateral boundaries, which are averaged over the region of the Tibetan Plateau. Unit is $K \cdot m^{-1} \cdot s^{-2}$. (a) The total PV flux and the components; (b) the PV transfers crossing north(N), south(S), west(W) and east(E) lateral boundaries; (c) the net PV transfers in the zonal and meridional directions.

isentropic surface. Cyclonic circulation is then produced in the lower layer near the ground over the Tibetan Plateau. However, the increase of the positive vorticity in the lower layer is limited by the friction and transient processes in the boundary layer. On the other hand, in the upper layers the negative PV produced by the diabatic heating is mainly balanced by the outward transfer of the negative PV to the surrounding area.

Through this study, we can come to some conclusions as follows.

(i) In the lower troposphere over the Tibetan Plateau, the positive PV produced by diabatic heating is balanced mainly by the friction and transient processes. In the upper layers over the Tibetan Plateau, the decrease in the diabatic heating with height generates a negative vorticity and maintains the Tibetan High. This negative PV generation is balanced mainly by the horizontal divergence of PV, making the Tibetan Plateau a strong negative vorticity source.

(ii) Within the air-column over the Tibetan Plateau, the surplus positive PV produced by the diabatic heating in the lower layer is transferred to the upper layer, where it partly offsets the negative PV generation due to the diabatic heating.

(iii) The analysis of the PV transfer crossing the lateral boundary over the Tibetan Plateau indicates that there is a net outward negative PV transfer crossing the eastern and northern lateral boundaries from the Tibetan Plateau region. Thus the air-column over the Tibetan Plateau is an important negative PV source in the atmosphere.

The results obtained from the study are different in some sense from those theoretical results of the thermal adaptation theory of Wu et al.[10]. In their theoretical model, there is an outward negative

PV flux from a heating region towards surrounding area crossing all the lateral boundaries in the upper layer of the heating domain, because their theoretical model is a solitary model of thermal adaptation, and there is no background flow field. In our case, there exists a strong background flow field in summer, and therefore the outward negative PV flux only appears at the eastern and northern lateral boundaries over the Tibetan Plateau. In the numerical experiment conducted by Liu et al.[11] the July background flows were taken into account, a negative vorticity source in the upper troposphere generated by the diabatic heating can generate Rossby wave train which propagates northwards and eastwards and affects the Northern Hemisphere circulation. This is in agreement with the result obtained in present study.

In this paper we only analyzed the impacts of the diabatic heating on the large-scale circulation over the Tibetan Plateau. Because of the geographical location of the Tibetan Plateau, the atmospheric circulation over the Tibetan Plateau is a complicated process. Moreover, it is also affected by the circulation at high-middle latitudes as well as those at low latitudes. All these need to be further investigated.

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