ABRUPT CHANGE OF QUASI-GEOSTROPHIC FLOW FORCED BY OROGRAPHY AND DIABATIC HEATING

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ABSTRACT

A low-order spectral model is used to study abrupt change of quasi-geostrophic current forced by both orography and diabatic heating. In certain parametric combinations, along with the gradual change of external thermal forcing, it is found that abrupt changes of both the spectral coefficient and the locations of the westerly jet stream can be stimulated.

Introducing the orography into the model results in a change of the parametric range in which the multiple equilibrium states in flow patterns exist and the shift of the parametric critical points at which the abrupt change of the locations of westerly jet streams is created, as well as increase of the wave components of the equilibrium flow patterns. The aspects of simulated "South Branch" jet streams are more similar to the observational fact in the presence of both the orography and the diabatic heating than those in the case of the heating forcing.

I. INTRODUCTION

Since Ye et al. (1958) put forward the observational fact about the abrupt change of the atmospheric circulation over the Northern Hemisphere in June and October, the problem concerning the abrupt change and its physical mechanism has been attracting one's wide attention. The abrupt change is a most important motion form in the atmospheric circulation. The investigation on its mechanism not only forms one of basic projects in nonlinear dynamic meteorology, but also comes to constitute one of theoretical bases of mid-range and long-range forecast methods.

Li and Luo (1983) regarded the system of the atmospheric circulation as a dissipative, nonlinear one forced by diabatic heating and probed into the nonlinear mechanism of the abrupt change of the atmospheric circulation in June and October.

As is well known, besides diabatic forcing, there is a mechanical forcing arisen from orography in the atmosphere. As early as 1950s, Zhu (1957) deeply studied the effects of both orography and diabatic heating on the atmospheric circulation. Previous studies regarding the physical mechanism of the seasonal abrupt change are all restricted to the atmosphere without taking account of orography. In the present paper we study the problem concerning the abrupt change of quasi-geostrophic current forced by a combination of both orographic and thermal forcing.

The averaged latitudinal location of the "South Branch" jet stream formed just after the jump from the summer half year to the winter one in the model atmosphere (Li and Luo, 1983) is close to that in the real atmosphere. However, the axis of the simulated jet stream is approximately parallel to the zonal cycle direction and does not branch. These results do not consist with the observational facts. We will try to explore whether the disagreement is connected to orographic effects.

II. MODEL

The equation of conservation of potential vorticity of a homogeneous β-plane atmosphere can be written as

$$\frac{\partial}{\partial t}\left(\nabla^2\psi-\frac{\psi}{\lambda^2}\right)+J\left(\psi,\nabla^2\psi-\frac{\psi}{\lambda^2}+f_0\frac{h}{H}+\beta y\right)=-\frac{f_0 D_E}{2H}\nabla^2(\psi-\psi^*) \quad , \qquad (1)$$

where $\psi=(g/f_0)\eta$ is the geostrophic stream function, g the gravitational acceleration, f_0 the Coriolis parameter at the central latitude φ_0 of the β-plane, $H+\eta$ the height of the free surface, H the mean height of the homogeneous atmosphere, h the lower boundary elevation, D_E the Ekman depth, ψ^* prescribed thermal forcing parameter, $\lambda^2=\frac{gH}{f_0^2}$ and $\beta=\left(\frac{df}{dy}\right)_{\varphi_0}$, with $\varphi_0=35°$ N and $H=10^6$ cm taken.

Suppose

$$\begin{aligned}&(t,x,y,\psi,\psi^*,h,\lambda,\beta)\\&=(f_0^{-1}t',Lx',Ly',L^2f_0\psi',L^2f_0\psi^{*\prime},Hh',L\lambda',f_0L^{-1}\beta'),\end{aligned} \qquad (2)$$

where L is the horizontal wavelength, and $L=1.77\times10^8$ cm.

Substituting (2) into (1), we obtain the nondimensional equation

$$\frac{\partial}{\partial t}\left(\nabla^2\psi-\frac{\psi}{\lambda^2}\right)+J(\psi,\nabla^2\psi+h)+\beta\frac{\partial\psi}{\partial x}+k\nabla^2(\psi-\psi^*)=0 \ , \qquad (3)$$

where $k=\frac{D_E}{2H}$, and primes have been omitted.

In Eq. (3), if the frictional term takes the place of $\nu\nabla^4\psi$ and letting $h=\lambda^{-1}=0$, then it is the same as formula (1) in the paper of Li and Luo (1983).

Setting $h=h_k\,2\sin y\cos nx$,

$$\begin{aligned}(\psi,\psi^*)=&(\psi_A,\psi_A^*)\sqrt{2}\cos y+(\psi_K,\psi_K^*)2\sin y\cos nx+(\psi_C,\psi_C^*)\sqrt{2}\cos 2y\\&+(\psi_N,\psi_N^*)2\sin 2y\sin nx,\end{aligned} \qquad (4)$$

and substituting (4) into (3), we obtain the spectral equations

$$\dot\psi_A=-k_{01}(\psi_A-\psi_A^*) \ , \qquad (5)$$
$$\dot\psi_K=-\delta_{n1}\psi_C\psi_N-k_{n1}(\psi_K-\psi_K^*) \ , \qquad (6)$$
$$\dot\psi_C=\varepsilon_n\psi_K\psi_N-k_{02}(\psi_C-\psi_C^*)+h_{02}\psi_N \ , \qquad (7)$$
$$\dot\psi_N=\delta_{n2}\psi_C\psi_K-k_{n2}(\psi_N-\psi_N^*)-h_{n2}\psi_C \ . \qquad (8)$$

The following values of parameters are taken as: $a''=\frac{64\sqrt{2}\,n}{15\pi}$, $k_{01}=\frac{k}{1+\lambda^{-2}}$, $k_{n1}=\frac{n^2+1}{n^2+1+\lambda^{-2}}k$, $k_{02}=\frac{4}{4+\lambda^{-2}}k$, $\delta_{n1}=\frac{n^2a''}{n^2+1+\lambda^{-2}}$, $\delta_{n2}=\frac{(n^2-3)a''}{n^2+4+\lambda^{-2}}$, $k_{n2}=\frac{n^2+4}{n^2+4+\lambda^{-2}}k$, $\varepsilon_n=\frac{3a''}{4+\lambda^{-2}}$, $h_{02}=\frac{a''h_K}{4+\lambda^{-2}}$, $h_{n2}=\frac{a''h_K}{n^2+4+\lambda^{-2}}$, where n is the zonal wavenumber in the β-plane.

ψ_i $(i=A,K,C,N)$ are divided into the stationary and the perturbational quantities.

According to Eqs. (5)—(8), the stationary quantities are governed by

$$\overline{\Psi}_A = \psi_A^* , \tag{9}$$

$$\delta_{n1}\overline{\Psi}_C\overline{\Psi}_N + k_{n1}\overline{\Psi}_K = k_{n1}\psi_K^*, \tag{10}$$

$$-\varepsilon_n\overline{\Psi}_K\overline{\Psi}_N + k_{02}\overline{\Psi}_C - h_{02}\overline{\Psi}_N = k_{02}\psi_C^*, \tag{11}$$

$$-\delta_{n2}\overline{\Psi}_C\overline{\Psi}_N + k_{n2}\overline{\Psi}_N + h_{n2}\overline{\Psi}_C = k_{n2}\psi_N^*, \tag{12}$$

Eqs. (9)—(12) may be solved and we obtain

$$\overline{\Psi}_K = \frac{k_{n1}k_{n2}\psi_K^* - \delta_{n1}k_{n2}\psi_N^*\overline{\Psi}_C + \delta_{n1}h_{n2}\overline{\Psi}_C^2}{\delta_{n1}\delta_{n2}\overline{\Psi}_C^2 + k_{n1}k_{n2}}, \tag{13}$$

$$\overline{\Psi}_N = \frac{k_{n1}k_{n2}\psi_N^* + k_{n1}\delta_{n2}\psi_K^*\overline{\Psi}_C - k_{n1}h_{n2}\overline{\Psi}_C}{\delta_{n1}\delta_{n2}\overline{\Psi}_C^2 + k_{n1}k_{n2}}. \tag{14}$$

And $\overline{\Psi}_C$ is determined by the equation

$$\sum_{j=0}^{5} A_j\overline{\Psi}_C^{5-j} = 0, \tag{15}$$

where

$$A_0 = k_{02}\delta_{n1}^2\delta_{n2}^2,$$

$$A_1 = -k_{02}\delta_{n1}^2\delta_{n2}^2\psi_C^*,$$

$$A_2 = \varepsilon_n\delta_{n1}k_{n1}h_{n2}^2 - \varepsilon_n\delta_{n1}\delta_{n2}k_{n1}h_{n2}\psi_K^* + 2k_{02}k_{n1}k_{n2}\delta_{n1}\delta_{n2} + h_{02}\delta_{n1}\delta_{n2}k_{n1}h_{n2} - h_{02}\delta_{n1}\delta_{n2}^2k_{n1}\overline{\Psi}_K^*,$$

$$A_3 = -2\varepsilon_nk_{n1}k_{n2}h_{n2}\delta_{n1}\psi_N^* + \varepsilon_nk_{n1}k_{n2}\delta_{n1}\delta_{n2}\psi_K^*\psi_N^* - h_{02}\delta_{n1}\delta_{n2}k_{n1}k_{n2}\psi_N^* - 2k_{n1}k_{02}k_{n2}\delta_{n1}\delta_{n2}\psi_C^* ,$$

$$A_4 = \varepsilon_n\delta_{n1}k_{n2}^2k_{n1}\psi_N^{*2} + \varepsilon_nk_{n1}^2k_{n2}h_{n2}\psi_K^* - \varepsilon_nk_{n1}^2k_{n2}\delta_{n2}\psi_K^{*2} + k_{02}k_{n1}^2k_{n2}^2 + h_{02}k_{n1}^2k_{n2}h_{n2} - h_{02}k_{n1}^2k_{n2}\delta_{n2}\psi_K^*,$$

$$A_5 = -\varepsilon_nk_{n1}^2k_{n2}^2\psi_K^*\psi_N^* - h_{02}k_{n1}^2k_{n2}^2\psi_N^* - k_{02}k_{n1}^2k_{n2}^2\psi_C^*.$$

ψ_A^* describes the thermal forcing between the equator and the pole along the y-direction. ψ_K^* approximately stands for the thermal forcing along the x-direction, including the thermal contrast between sea and land. The thermal forcing with respect to the second y-direction mode, which includes the thermodynamic contrast between the subtropical continent and plateau and the ocean south of them, is roughly represented by ψ_C^*. In consideration of the geographical location of East Asia, if $\psi_C^* < 0$, it generally corresponds to summer half year, if reverse, the winter one. When $\psi_C^* = 0$, it roughly corresponds to the period of transition between summer half year to winter one. In other words, when ψ_C^* varies gradually from negative to positive it can roughly represent the evolution of the diabatic heating field from summer to winter. As a simplification, it may be assumed that $\psi_N^* = 0$.

Eqs. (9)—(12) pose the forced, dissipative, and nonlinear system with unknown variables $\overline{\Psi}_A, \overline{\Psi}_K, \overline{\Psi}_C$, and $\overline{\Psi}_N$. The system contains both the thermal and orographic forcing. Because of the nonlinearity, under the same prescribed forcings, Eq. (15) probably has non-unique solutions of $\overline{\Psi}_C$; if so, substituting the non-unique solutions of $\overline{\Psi}_C$ into (13) and (14) can obtain non-unique solutions of $\overline{\Psi}_K$ and $\overline{\Psi}_N$. In addition, it can be seen from (14) that $\overline{\Psi}_N$ is not equal to zero though $h_N = \psi_N^* = 0$, which is obviously due to the nonlinear interaction among various spectral components.

According to the perturbational equation system, the characteristic equation is

$$\begin{vmatrix} k_{n_1}+\sigma & \delta_{n_1}\overline{\Phi}_N & \delta_{n_1}\overline{\Phi}_C \\ -\varepsilon_n\overline{\Phi}_N & k_{02}+\sigma & -\varepsilon_n\overline{\Phi}_K-h_{02} \\ -\delta_{n_2}\overline{\Phi}_C & h_{n_2}-\delta_{n_2}\overline{\Phi}_K & k_{n_2}+\sigma \end{vmatrix}=0. \tag{16}$$

Eqs. (16) will be used to determine whether the equilibria are stable.

III. ABRUPT CHANGE FORCED BY A COMBINATION OF OROGRAPHIC AND THERMAL FORCING IN THE MODEL ATMOSPHERE

Abrupt change is always related to the equilibria of systems. Therefore, we ought to find out the parametric ranges where equilibria exist. It can be seen from (13)—(15) that the stationary solutions $\overline{\Phi}_K, \overline{\Phi}_N$ and $\overline{\Phi}_C$ depend on both thermal and orographic forcing parameters, thus they are the equilibrium solutions under the action of a combination of orographic and thermal forcings. In the meanwhile, we can see from (16) that the stabilities of the stationary solutions are also connected with the orographic forcing parameters.

Eq. (15) is a five order equation of $\overline{\Phi}_C$. It can only be solved by numerical methods. The specified values of the parameters are taken: $n=2$, $k=0.025$, $h_K=0.05$, 0.00, $(\psi_K^*, \psi_C^*)=-0.200$, -0.198, -0.196, …, 0.196, 0.198, 0.200. The numbers of real roots of $\overline{\Phi}_C$ are computed from Eq. (15) by use of the iteration method. The computational results are shown in Fig. 1. There are three real roots in the two regions above curve A′O′B′ and below curve AOB and only one real root in the intermediate region, when $h_K=0.05$. However when $h_K=0$, there is one root in the region between AOB and A″O″B″ and three real roots in the other regions.

Solving Eq. (15), then substituting the solutions of $\overline{\Phi}_C$ into (13) and (14) and using Eq. (9), we obtain the solutions $\overline{\Phi}_K, \overline{\Phi}_N$, and $\overline{\Phi}_A$ that are three equilibrium states $(\overline{\Phi}_A, \overline{\Phi}_K, \overline{\Phi}_C, \overline{\Phi}_N)$ in flow patterns. Then we use Eq. (16) to determine whether the equilibrium states $(\overline{\Phi}_A, \overline{\Phi}_K, \overline{\Phi}_C, \overline{\Phi}_N)$ are stable. The computational results concerning the equilibrium states and their stabilities are as follows. If $\psi_C^* \leqslant -0.024$, there appears one stable equilibrium state in flow patterns with value of $\overline{\Phi}_C$ being negative. When $|\psi_C^*| \leqslant 0.022$, which corresponds to the period of seasonal transition, two stable equilibria exist. When $\psi_C^* \geqslant 0.024$, there occurs one stable equilibrium state in flow patterns with value of $\overline{\Phi}_C$ being positive (see Table 1, Fig. 2).

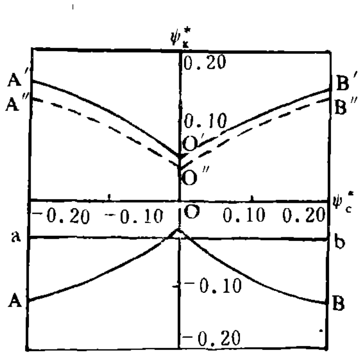

Fig. 1. Distribution of number of the real roots $\bar{\psi}_C$.

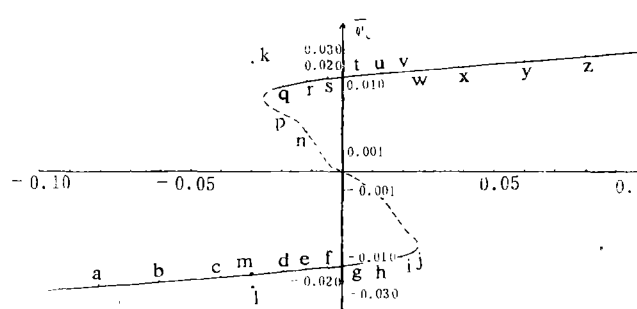

Fig. 2. Variation of $\bar{\psi}_C$ with ψ_C^* ($n=2$, $k=0.025$, $h_K=0.05$, $\psi_K^*=-0.05$; Dashed lines denote unstable equilibria and solid lines stable equilibria).

Table 1. Equilibrium Solutions of $\bar{\psi}_C$ ($n=2$, $k=0.025$. $h_K=0.05$, $\psi_K^*=-0.05$; Δ represents the unstable solution)

ψ_C^*	-0.080	-0.060	-0.040	-0.026	-0.024	-0.022	-0.020	-0.012	-0.004
$\bar{\psi}_C$					0.0076^{Δ}	0.0084	0.0090	0.0107	0.0120
					0.0050^{Δ}	0.0042^{Δ}	0.0036^{Δ}	0.0020^{Δ}	0.0006^{Δ}
	-0.0243	-0.0208	-0.0179	-0.0161	-0.0158	-0.0155	-0.0153	-0.0142	-0.0131
ψ_C^*	0.004	0.012	0.020	0.022	0.024	0.026	0.040	0.060	0.080
$\bar{\psi}_C$	0.0131	0.0142	0.0153	0.0155	0.0158	0.0161	0.0179	0.0208	0.0243
	-0.0006^{Δ}	-0.0020^{Δ}	-0.0036^{Δ}	-0.0042^{Δ}	-0.0050^{Δ}				
	-0.0120	-0.0107	-0.0090	-0.0084	-0.0076^{Δ}				

For the sake of convenience, we call segments ai, jp and qz in Fig. 2 the bottom, middle and top pleat, respectively. Below we discuss the evolution of $\bar{\Phi}_C$ along with the gradual change of $\bar{\Phi}_C^*$. When $\psi_C^*=-0.08$, which corresponds to the point a of the bottom pleat and roughly denotes a period of time in midsummer, there is only one equilibrium solution $\bar{\Phi}_C=-0.0243$, which is stable. From summer to autumn, the value of $|\psi_C^*|$ decreases gradually; through the points b, c and m in the bottom pleat, the system has always one equilibrium which is stable and the value of $\bar{\Phi}_C$ is also gradually variable. From the point d through the points e, f, g, h to the point i, the system gets into the region where the three equilibrium states in flow patterns lie. The two equilibria corresponding to the bottom and the top pleats are all stable, but the other corresponding to the middle pleat having reflective property is unstable. Because of the instability of the middle pleat, the stable system state situated on the point d of the bottom pleat neither can jump over the middle pleat, nor can directly get into the top pleat, but only can shift gradually along the bottom pleat in the way d→e→f→g→h→i, with the gradual change of ψ_C^* from -0.024 to 0.022. When ψ_C^* increases continuously and achieves 0.024, the system state jumps rapidly from the point i on the bottom pleat to the point w on the top pleat. This rapid jumping results from that when $\psi_C^*=0.024$, there are the three equilibria of $\bar{\Phi}_C$, two of them is unstable, and only one stable $\bar{\Phi}_C=0.0158$ (see Table 1). Therefore, the abrupt change of $\bar{\Phi}_C$ can be stimulated by the gradual change of the thermal forcing parameter ψ_C^*.

The abrupt change of $\bar{\Phi}_C$ implies the abrupt change of the location of the westerly jet stream. The distributions of the westerly components averaged along the zonal circle with latitudes and the latitudinal locations where the westerly components achieve their maxima, corresponding to the points a,b,c,d,$\cdots$, x,y,z on the curve in Fig. 2, are shown in Fig. 3. Obviously, at the points a,b,c,d,$\cdots$, i,j, on the bottom pleat, the corresponding locations of the westerly jet streams averaged along the zonal circle are always situated to north of 40° N, it forms the situation of "North Branch" jet stream. On the other hand, at the points q,r,s,t, u,v,w,..., z on the top pleat, the corresponding locations of the westerly jet streams are always located south of 30°N and there appears the situation of "South Branch" jet stream. Overstepping rapidly from the point i right away to the point w is equivalent to the abrupt establishment of "South Branch" jet stream from summer half year to winter one. In the meantime, we also compute the geostrophic wind velocity field in the β-plane corresponding to those points on the curve (figures omitted). When the system is situated at the point i, the latitudinal location of the jet stream averaged in the longitudinal range of the model plateau is near 40° N, but for the system at the point w, it is near 20° N.

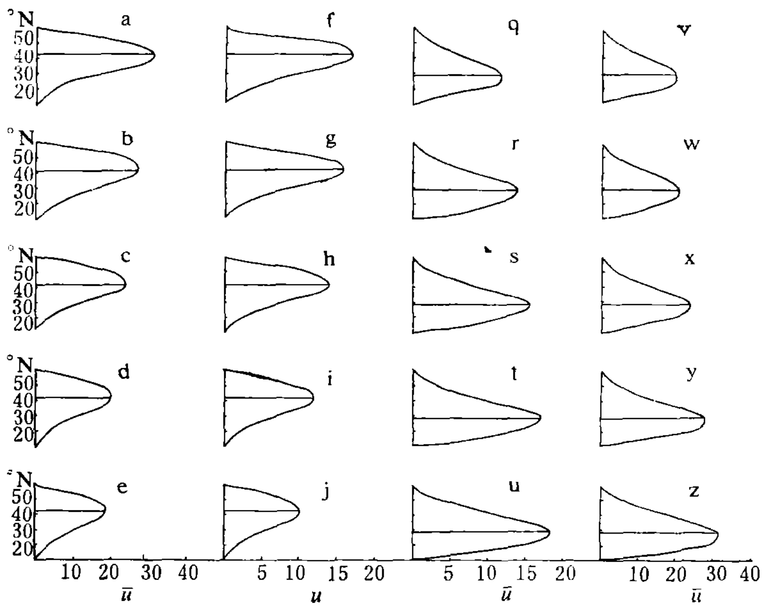

Fig. 3. Distributions of west wind velocities averaged along zonal circle $\bar{u}$ with latitudes ($n=2$, $k=0.025$, $h_K=0.05$, $\psi_K^*=-0.05$, unit of wind velocity is m s^{-1}).

In order to further confirm the above-mentioned computations about solving five-order Eq. (15) and characteristic Eq. (16), three kinds of numerical integrations, by using the low-order spectral system (5)—(8), have been performed.

(1) Letting $\psi_C^*=-0.08$, which corresponds to the point a on the bottom pleat, then $\bar{\psi}_{Ca}=-0.0243$ (Table 1). Substituting that value of $\bar{\psi}_C$ into (13) and (14),we can yield $\bar{\psi}_{Ka}$ and $\bar{\psi}_{Na}$. Starting from $(\bar{\psi}_{Ca}, \bar{\psi}_{Ka}, \bar{\psi}_{Na})$ as initial values and having integrated Eqs. (5)—(8) to the 300 th model day or later, we find that in the process of the integration ψ_C, ψ_K and ψ_N all maintain invariant. In addition, setting $\psi_C^*=-0.03$, because there is only one stable equilibrium there, the system should situate at the point m; starting from two groups of initial values corresponding to the point k and l in Fig. 2, respectively, the integration results manifest that the system is all quickly attracted to the point m. These results confirm the stabilities of those states situated on the bottom pleat having the absorbed properties.

(2) Setting $\psi_C^*=-0.05$, which corresponds to the point b in Fig. 2, and starting from the initial value at the point a, the integration results show that the system is attracted to the state at the point b. Similarly, letting $\psi_C^*=-0.04$, -0.02, -0.01, which corresponds to the points c, d, h in Fig. 2, starting from the initial values at the points b, c, d, the system reaches the states at the point c, d, h, respectively. Thus, the system certainly shifts along

the bottom pleat in the way a→b→c→d→h.

(3) Taking $\psi_C^*=0.024$, which corresponds to the point j in Fig. 2, and also the initial condition at the point j. In the process of the integration, the system certainly oversteps from the point j to w at once.

To sum up, we think that in the certain parametric range along with the gradual change of the thermal forcing parameter, the quasi-geostrophic current forced by both orography and diabatic heating reliably possesses the behaviour of the abrupt change.

IV. EFFECTS OF OROGRAPHY ON MULTIPLE EQUILIBRIA AND ABRUPT CHANGE IN FLOW PATTERNS

For one thing, we will discuss the effects of orography on multiple equilibria in flow pattern in terms of Eqs. (13)—(15). It can be seen from Eqs. (13) and (14) that the spectral component $\bar{\Phi}_K$, as well as $\bar{\Phi}_N$ consists of three terms. The first two terms are directly related diabatic effects and hereinafter their sum is referred to as $(\bar{\Phi}_i)_q$ $(i=K,N)$. The third term results from orography and hereinafter it is represented by $(\bar{\Phi}_i)_h$ $(i=K,N)$.

The following parametric values are taken; $\psi_C^*=-0.05$, -0.025, 0.025, 0.05, $\psi_K^*=-0.04$, 0.04, $k=0.025$, and $h=0.05$, 0.00. By using Eqs. (13)—(15), the values of $(\bar{\Phi}_i)_q$ and $(\bar{\Phi}_i)_h$ were computed. The results exhibit that $O((\bar{\Phi}_i)_q)\approx O((\bar{\Phi}_i)_h)$, which means that the effects of orography on $\bar{\Phi}_K$ and $\bar{\Phi}_N$ can not be neglected. When $\psi_K^*=-0.04$, the computation results about $(\bar{\Phi}_i)_q$ and $(\bar{\Phi}_i)_h$ are given in Table 2.

Table 2. Computation Results of $(\bar{\psi}_i)_q$, $(\bar{\psi}_i)_h$, L_{qh} and L_q

ψ_C^*	$(\bar{\psi}_K)_q$	$(\bar{\psi}_K)_h$	$\bar{\psi}_K$	$(\bar{\psi}_N)_q$	$(\bar{\psi}_N)_h$	$\bar{\psi}_N$	L_q	L_{qh}
−0.050	−0.0051	0.0165	−0.0009	0.0053	0.0093	0.0176	0.0074	0.0176
−0.025	−0.0108	0.0062	−0.0110	0.0071	0.0065	0.0166	0.0129	0.0199
0.025	−0.0108	0.0062	−0.0110	−0.0071	−0.0065	−0.0166	0.0129	0.0199
0.050	−0.0051	0.0165	−0.0009	−0.0053	−0.0093	−0.0176	0.0074	0.0176

In the expressions of coefficients for Eq. (15), there are also orographic parameters h_{02} and h_{n2}. Therefore, after introducing orography into the model, the solutions of $\bar{\Phi}_C$ are different from those in the case without orography, it may change the values of $\bar{\Phi}_K$ and $\bar{\Phi}_N$ and results in that $\bar{\Phi}_i \neq (\bar{\Phi}_i)_q+(\bar{\Phi}_i)_h$ in Table 2. The values of L_{qh} and L_q are also shown in Table 2, with, $L_{qh}=\sqrt{\bar{\Phi}_K^2+\bar{\Phi}_N^2}$, $L_q=\sqrt{(\bar{\Phi}_K)_q^2+(\bar{\Phi}_N)_q^2}$. L_{qh} and L_q represent the intensity of wave components of flow patterns under the forcings of both orography and diabatic heating and the forcing alone of diabatic heating, respectively. It is obvious that $L_{qh}>L_q$ (see Table 2) showing that introducing orography into the model can increase the intensity of wave components of flow patterns.

The variation in intensity of wave components of flow patterns can directly change the situation of "South Branch" jet stream formed just after the abrupt jump from summer half year to winter one. In the absence of orography the jet stream swings within the range of about five latitudes, and it is nearly parallel to the zonal circle. In the presence of both orography and diabatic heating, the latitudinal range in which the jet stream fluctuates obviously enlarges and achieves (10—15) latitudes, and the jet stream branches near 50°N (Fig. 4). This is similar to the observational fact (see Figs. 1—9a, CMB, 1975).

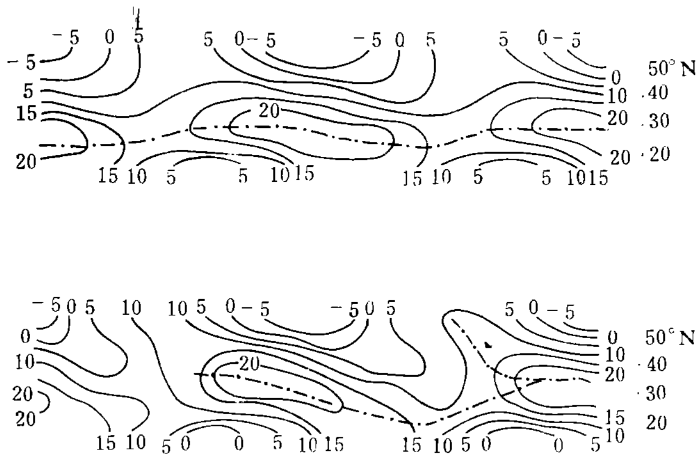

Fig. 4. Zonal wind component fields.
$h_K = 0$ (top), $h_K = 0.05$ (bottom), $n=2$, $k=0.025$,
$\psi_K^* = -0.05$ and $\psi_C^* = -0.012$.

As mentioned above, the coefficients of Eq. (15) contain orographic parameters. Thus, introducing orography into the model can change the range of the thermal parameters when there appear three real roots of $\overline{\Psi}_C$, namely, it can change the parametric ranges of multiple equilibria (see Fig. 1).

The existence of multiple equilibria is a necessary condition for stimulating the abrupt change. Since introducing orography can change the parametric ranges of multiple equilibria, it should be able to shift the critical values of parameters over which the abrupt changes occur. In the cases with and without orography, in the range of $-0.10 \leqslant \psi_C^* \leqslant 0.10$, we computed the stationary solutions $\overline{\Psi}_C, \overline{\Psi}_K, \overline{\Psi}_N$ and their stabilities by use of Eqs. (13)—(16). The results manifest that in the absence of orography, the critical value of ψ_C^* at which the seasonal jump from summer half year to winter one occurs is equal to 0.020, but in the presence of it, that equals 0.024, which exhibits the effect of orography on the abrupt change of flow pattern.

V. CONCLUSIONS AND DISCUSSIONS

Recently, the preliminary results regarding the nonlinear mechanism of the abrupt change of the atmospheric circulation have been yielded (Li and Luo, 1983). However, the model used in their paper is of high simplification. It is a problem to be solved that whether the abrupt change in flow patterns can still hold well in the model atmosphere after the new physical processes are introduced into it one by one. In this paper an ideal orography has been added. Using the modified model, we also obtain the abrupt change of the atmospheric circulation. The situation of "South Branch" jet stream formed just after the abrupt change from summer half year to winter one is more similar to the observational facts in the presence of orography than that in the absence of it.

Abrupt change is a most important motion form of forced, dissiptative and nonlinear systems including the atmospheric circulation. Generally speaking, a nonlinear system describing the atmospheric circulation contains more than three dependent variables and the rapid variation in one or two of them often creates the obvious change of global properties. It therefore is possible that one or two state variables of the system can be found out to reflect the main characteristics of the global behaviour. Thus, as a mathematical tool, we may use the catastrophe theory in order to analyse some practical problems of the atmospheric circulation. On the other hand, because of the complexity of the physical processes existing in the real atmosphere, other theories and methods in dynamics are also necessary. It seems that a combination of the catastrophe theory and other dynamic theories will be profitable for studying further the abrupt change of the atmospheric circulation.

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