WAVE–MEAN FLOW INTERACTION AND FORMATION OF BLOCKING——PERSISTENT ANOMALOUS WEATHER IN CHINA IN THE SUMMER OF 1980 *

Wu Guoxiong (吴国雄), *Liu Hui* (刘 辉), *Chen Fei* (陈 飞), *Zhao Yucheng* (赵宇程)

State Key Lab of Atmospheric Sciences and Geophysical Fluid Dynamics (LASG), Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100080

and *Lu Ying* (卢 莹)

Provincial Weather Bureau of Henan, Zhengzhou 450003

Received February 8, 1995

ABSTRACT

In the summer of 1980, serious persistent abnormal weather occurred over vast areas in China. While record–breaking cold and flood were observed in the reaches of the Changjiang and Huaihe Rivers, severe hot wave and drought dominated the entire northern China. The long–lasting disastrous weather is mainly due to the stable development and maintenance of blocking anticyclone over the northeastern Asia. This study aims at the understanding of the roles of time–varying weather system transport in the formation of the blocking.

It was shown that during this period, there appeared continuous generation of synoptic–scale perturbations along the strong baroclinic zone over Europe and the western Asia. While such perturbations propagated eastward, energy conversion occurred. At equivalent barotropic layer, with weak dissipation, such energy conversion was subjected to the so–called bi–directional principle: while the energy of the synoptic–scale system cascaded to smaller scale system, a much larger portion was transferred to the blocking system with larger scale. Potential vorticity diagnoses also revealed that the transient weather systems played the roles of maintaining the mean anticyclonic vorticity to the south, and mean cyclonic vorticity to the north, of the westerly jet, and exciting strong anticyclonic vorticity growth and corresponding geopotential height increase in high latitude area downstream of the westerly diffluence region.

The research also showed that, the intensity of the forcing of the blocking formation via wave–mean flow interaction in this Asian case was much stronger than that occurring in the western Europe in the summer of 1976. It was therefore concluded that when persistent abnormal weather in the northern China was studied, in addition to the subtropical weather systems, attention should also be drawn to the development of baroclinic zone over Europe and the western Asia, and the propagation and transfer properties of the synoptic systems embedded in the baroclinic zone.

Key words: transient eddy, formation of blocking high, anomalous weather

I. INTRODUCTION

In the summer of 1980, an unusual persistent weather pattern of severe flood in south and drought in north occurred in China (Fig. 1). In the area south of the Huanghe River and north of the Changjiang River, there were serious cold and torrential rains. During June and July, in

* This study was supported by the State Key Program for Fundamental Research "Climate dynamics and prediction theory".

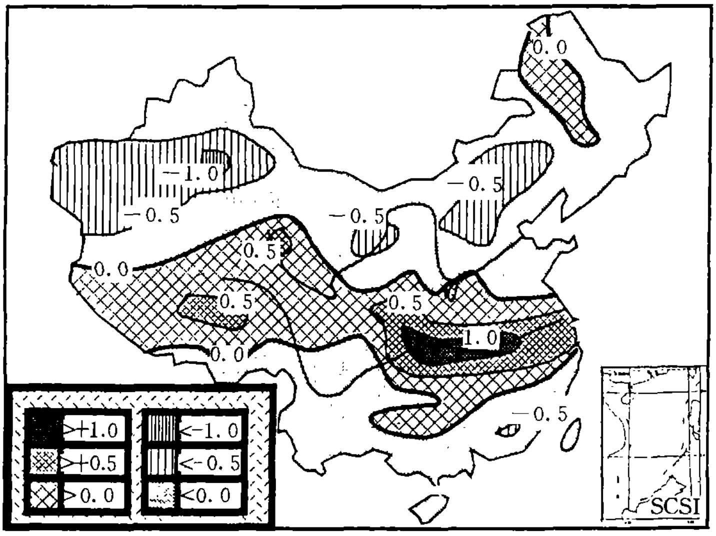

Fig. 1. Distribution of rainfall anomaly in percentage during the period between June and August, 1980. Heavy solid curve denotes zero anomaly. Graded shading area indicates positive, otherwise negative. Contour interval is 0.5.

the areas of Changjiang–Huaihe Rivers, Huanghe–Huaihe Rivers, and Hanshui Rivers, the air temperature was 2°C below the normal, and the rainfall was two times as much as the average (Jiao and Wang 1980; Chen and Xue 1980). This became more serious in August. In the areas of Shanghai, Nanjing, and Wuhan cities, record breaking colds were observed, and rainfall was 1—3 times more than the normal. Along the whole reaches of the Changjiang River, the extraordinary flood was only next to that in 1954 since 1949. In the same period, the area north of the Huanghe River experienced persistent hot and drought climate. In June, the maximum temperature as high as 35—39°C appeared in Northeast China and Inner Mongolia. In July, the monthly average temperature of the vast areas of Inner Mongolia was 2—3°C above the average. During the period, rainfall in the middle and lower reaches of the Huanghe River and in Northeast China decreased by 20%—50% compared to the normal, and by 50%—80% in North and Northwest China with a total of only 10—40 mm, which had been seldom during the past sixty years. Beijing recorded her extreme minimum rainfall of 31 mm since observation records started in 1895. In August, the northern drought developed further. The persistence and seriousness of the anomalous weather over a vast area are really rare in history.

Bi and Ding (1993) analysed the weather situation of this summer, and pointed out that the above mentioned persistent anomalous weather was associated with the stable maintenance of blocking high in the Northeast Asia region. The purpose of this study is to understand the mechanism forming the blocking high.

There exist two different viewpoints about the formation of blocking high. One regards it as a response to global forcing; the other as a response to neighbourhood forcing. The latter has been receiving more and more attention. As a matter of fact, many researchers, as early as in the 1940s and 1950s, had noticed the contributions of the upstream baroclinic unstable perturbation to the formation of downstream blocking (e.g., Berggern et al. 1949; Gu et al. 1957; Ye et al. 1962; Namias 1964). In general, orographically forced perturbation tilts westward with increasing altitude, and thermally forced perturbation possesses out–of–phase structure between the upper and the lower circulations. However, blocking high which is warm and accompanied with low potential vorticity possesses equivalent barotropic structure. One reasonable explanation for the formation of the blocking high proposed by Green (1977) is that transient eddies in the upper layer continuously transfer negative vorticity towards the blocking centre, which can generate anticyclonic circulation in a few days. At the same time, the strong westerlies around the northern rim of the anticyclone converge towards the centre due to the Coriolis force. Air column then sinks and gets warming, and the lower layer anticyclonic circulation is formed due to forced divergence. A warm and equivalent barotropic blocking high is thus excited. This has been confirmed later by the diagnostic studies of Austin (1980) and Illari (1984), and by the numerical study of Shutts (1983), who introduced a "synoptic wave maker" into an equivalent barotropic model and successfully generated a blocking high.

In the present study, the neighbourhood forcing theory will be employed to investigate the formation of the blocking high occurring in Northeast Asia in 1980. Section II is designed to explain the roles of transient eddies in the formation of time–mean blocking flow. In Section III, the main characteristics of the atmospheric circulation in the summer of 1980 are described briefly. The spatial distribution of energy sources and sinks of synoptic scale systems at the equivalent barotropic layer is analysed in Section IV. The energy upscale cascade of synoptic scale perturbations towards blocking system is explored in Section V. Section VI is reserved for the discussion of interaction between transient eddies and time mean westerly jet, and the formation of the blocking high. Discussions and conclusions are presented in Section VII.

II. BASIC THEORY

The equivalent barotropic potential vorticity equation may be written as

$$\frac{\partial q}{\partial x} + \mathbf{V} \cdot \nabla q = F, \tag{1}$$

where F denotes forcing term, q is potential vorticity defined as

$$q = \nabla^2 \psi + f - \gamma^2 \psi,$$

γ, deformation radius satisfying $\gamma^2 = f^2 (gH)^{-1}$.

Splitting Eq. (1) into time–mean (denoted by "–") and transient (denoted by "′") parts, and neglecting higher order small terms, one gets

$$\frac{\partial \bar{q}}{\partial t} + \bar{\mathbf{V}} \cdot \nabla \bar{q} = - \nabla \cdot (\overline{\mathbf{V}'q'}) + \bar{F}, \tag{2}$$

$$\frac{\partial q'}{\partial t} + \bar{\mathbf{V}} \cdot \nabla q' + \mathbf{V}' \cdot \nabla \overline{q'} = F'. \tag{3}$$

Let transient enstrophy E_e and time–mean enstrophy $\bar{E}$ be

$$E_e = \frac{1}{2}\overline{(q')^2}, \qquad \bar{E} = \frac{1}{2}(\bar{q})^2, \tag{4}$$

respectively, then from Eq. (3) we get

$$\frac{\partial E_e}{\partial t} + \bar{\mathbf{V}} \cdot \nabla E_e + \overline{\mathbf{V}'q'} \cdot \nabla \bar{q} = \overline{F'q'}. \tag{5}$$

Let $\bar{\psi} = \bar{\psi}(\bar{q})$ and define a residual flux of transient eddy potential vorticity as

$$(\overline{\mathbf{V}'q'})_* = \overline{\mathbf{V}'q'} - \mathbf{k} \times \nabla \left(\frac{d\overline{\psi}}{d\overline{q}} E_e \right). \tag{6}$$

We then obtain a set of equations presenting the time variations of time– mean potential vorticity and transient enstrophy as

$$\frac{\partial \overline{q}}{\partial t} + \overline{\mathbf{V}} \cdot \nabla \overline{q} = - \nabla \cdot (\overline{\mathbf{V}'q'}) + \overline{F}, \tag{7}$$

$$\frac{\partial E_e}{\partial t} + (\overline{\mathbf{V}'q'})_* \cdot \nabla \overline{q} = \overline{F'q'}, \tag{8}$$

respectively. The above equations contain the term contributing to the time–mean field due to transient eddy transfer ($-\nabla \cdot \overline{\mathbf{V}'q'}$) and the term contributing to the transient eddy enstrophy due to the disposition of transient and time–mean fields ($(\overline{\mathbf{V}'q'})_* \cdot \nabla \overline{q}$); therefore, they can be used to study the contributions of transient eddy transfer to the development and maintenance of the persistent time–mean circulation.

III. GENERAL CIRCULATION PATTERN

On June 6, 1980, as the ridge of the western Pacific subtropical high jumped from 18°N to 22°N, and the rapid development of depression over the Bay of Bengal, the pre–monsoon rainfall in South China ended, and the mei–yu period in the reaches of Changjiang and Huaihe Rivers started. Since then, the position of the subtropical high had become very stable, and detained at 22°N. The Bengalis depression remained stronger than the normal. These resulted in the persistent maintenance of the rain belt in the Changjiang River and the Huaihe River regions. In addition to such subtropical circulation anomalies, the anomalous weather pattern is also associated with the persistent maintenance of blocking high in middle and high latitudes. The analyses of Bi and Ding (1993, referred to their Figs. 5 and 6) showed that in the early and middle July of 1980, the Northeast Asian blocking experienced re–development and establishment. From the middle of July to August, it maintained in the area between 110 and 150°E. Figures 2a and 2b showed the synoptic situation respectively of the 500 hPa and 700 hPa geopotential height at 0000 UT averaged over the period from July 15 to July 25. They are of representative of the entire summer mean situation (Jiao and Wang 1980; Dong and Xu 1980). During this period, the mid– and high–latitude West Asian trough was located in 60—80°E, shifting westward compared with the average; while the East Asian trough eastward shifted compared with the average (Fig. 2a). There was a stable blocking high maintained between these two troughs. A strong baroclinic zone extended eastward from the western coast of Europe to the west of Lake Baikal, then split into two branches. The northern branch surrounded the northern rim of the blocking, then flowed towards the Kamchaka Peninsula. The southern branch formed an anticyclonic circulation over the Mongol and Hetao region (the Old Bed of Huang), resulting in the persistent hot and drought weather in North China. At 700 hPa (Fig. 2b), small perturbations propagated southeastward along the southern westerly baroclinic zone and passed through the Hexi Corridor. They brought continuously cold air to meet southwesterlies from the Bay of Bengal, resulting in cold and flooding in the reaches of the Changjing and Huai Rivers.

In order to study the roles of the synoptic–scale eddies in the formation of the blocking high, we select the period of July 7—15 for diagnosis. The reasons for selecting this period

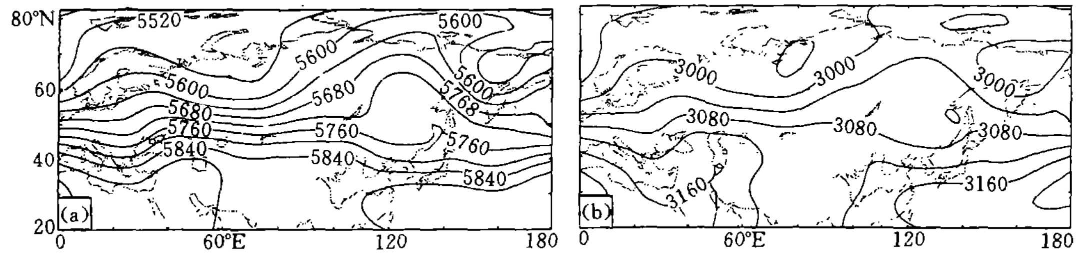

Fig. 2. Time mean 0000 UT weather chart for the period of July 15—25, 1980. Contour interval is 10 gpm. (a) 500 hPa, (b) 700 hPa.

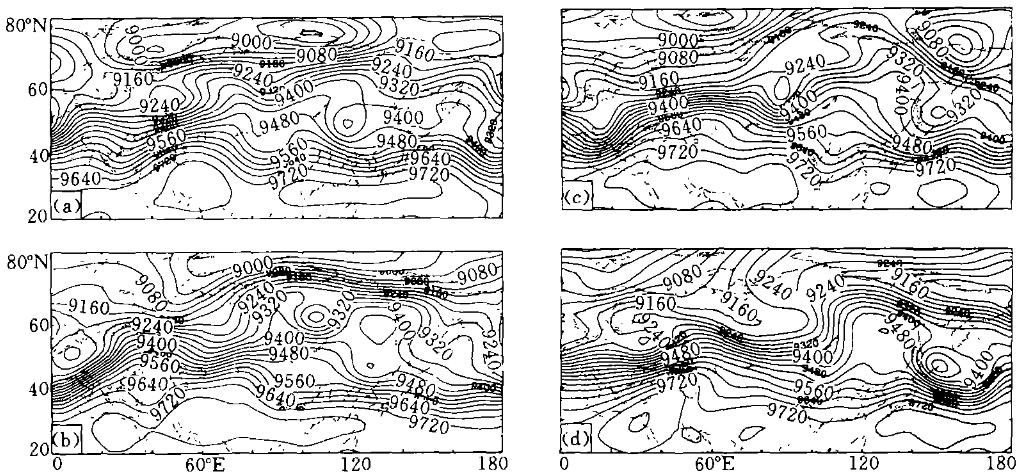

Fig. 3. Distribution of the 0000 UT geopotential height at 300 hPa on July 8 (a), 10 (b), 12 (c), and 14 (d), 1980, respectively.

(9 days) are as follows.

(1) The temporal evolution of daily synoptic situation during the period (Fig. 3) showed that the Northeast Asian blocking experienced a complete formation and development.

(2) There existed continuous development of synoptic systems in Europe and West Asia, which propagated eastward along a baroclinic zone. In the diffluence region near Lake Baikal, they split and propagated northeastward and southeastward, respectively.

(3) After this period, the blocking situation became steady. The monthly mean situations in July and August were very similar to those shown in Fig. 2.

In the following study, we will employ the ECMWF data achieved at the Data Center of Institute of Atmospheric Physics (DCIAP) for our analysis. The 300 hPa will be treated as an equivalent barotropic layer, and Eqs.(7) and (8) will be employed. In order to separate synoptic waves, all the time varying data have been processed by using a band–passed filter of 2.5—6 days (Blackmon 1976). In the following text, the word "perturbation" or "eddy" is used for those waves with a period of 2.5—6 days unless otherwise mentioned.

IV. ENERGY GENERATION AND DISSIPATION OF SYNOPTIC SCALE SYSTEMS

Figure 4 shows the distributions of transient eddy enstrophy E_e (Fig. 4a) and kinetic energy ($\overline{(V')^2}/2$) at 300 hPa averaged over the period of July 7—15, 1980. From the figure we can observe the following remarkable features:

(1) The maxima of both perturbation enstrophy and kinetic energy are embedded in the strong baroclinic zones from Europe to West Asia and over the western Pacific their minimum is in the region of blocking over the northern China and northeastern Asia .

(2) Along the eastward propagation track of the synoptic system, the perturbation enstrophy and kinetic energy possess relatively maximum. The meridional scale of these maximum areas increases eastward. Near the diffluent point (90°E, 50°N), the maximum area is divided into north and south branches as well. This means that the meridional scale of the synoptic systems extends when they propagate eastward along the diffluence field, resulting in the increase of north–south transfer.

When the scale of the time for research is much larger than the life cycle of the cyclone, or equals to the period of time averaging , then the tendency of E_e becomes very small, and Eq.(8) may be written as

$$(\overline{\mathbf{V}'q'})_* \cdot \nabla \bar{q} \simeq \overline{F'q'}. \tag{9}$$

Then, at the place where the direction of residual flux of perturbation potential vorticity is the same as the up–gradient of mean potential vorticity, ie., ($(\overline{\mathbf{V}'q'})_* \cdot \nabla\bar{q}) > 0$, the forcing sources F' and q' are positively correlated, and a perturbation enstrophy source exists. On the contrary, at the place where ($(\overline{\mathbf{V}'q'}) \cdot \nabla \bar{q}) < 0$, there exists a perturbation enstrophy sink. Figure 5 shows the disposition of $(\overline{\mathbf{V}'q'})_*$ and $\bar{q}$. From this figure, we see that in the regions of 20—50°E, 50—60°N; near the Lake Balkhash and Northwest of Lake Baikal there are the three main source regions along the mid.latitude westerlies. Downstream of these sources, there also occur the local maxima of perturbation enstrophy E_e (Fig. 4a) and kinetic energy K_e (Fig. 4b). On the daily weather charts, when passing over the Aral Sea, the Lake Balkhash and the Lake Baikal, the synoptic systems were either enhanced in intensity or decreased in scale, which were generally in consistent with the distribution of the above source regions.

The perturbation enstrophy sinks appeared near 60°E, 90°E, particularly 110°E. When approaching these regions, both the perturbation enstrophy (Fig. 4a) and the kinetic energy (Fig. 4b) decreased noticeably. In other words, after perturbation is generated along the strong baroclinic zone in Europe and in West Asia, it also subjects to energy dissipation during its eastward propagation. Its enstrophy dissipation becomes even more remarkable during its passage through the diffluence flow.

V. ENERGY CASCADE OF TRANSIENT EDDIES AND FORMATION OF BLOCKING HIGH

Let

$$\frac{\mathrm{d}}{\mathrm{d}t} = \frac{\partial}{\partial t} + \mathbf{V} \cdot \nabla , \tag{10}$$

be the material variation. In non–dissipation case, Eqs.(5) and (7) become

$$\frac{\mathrm{d}E_e}{\mathrm{d}t} + \overline{\mathbf{V}'q'} \cdot \nabla \bar{q} = 0, \tag{11a}$$

$$\frac{\mathrm{d}\bar{E}}{\mathrm{d}t} - \overline{\mathbf{V}'q'} \cdot \nabla \bar{q} + \nabla \cdot (\bar{q}\overline{\mathbf{V}'q'}) = 0, \tag{11b}$$

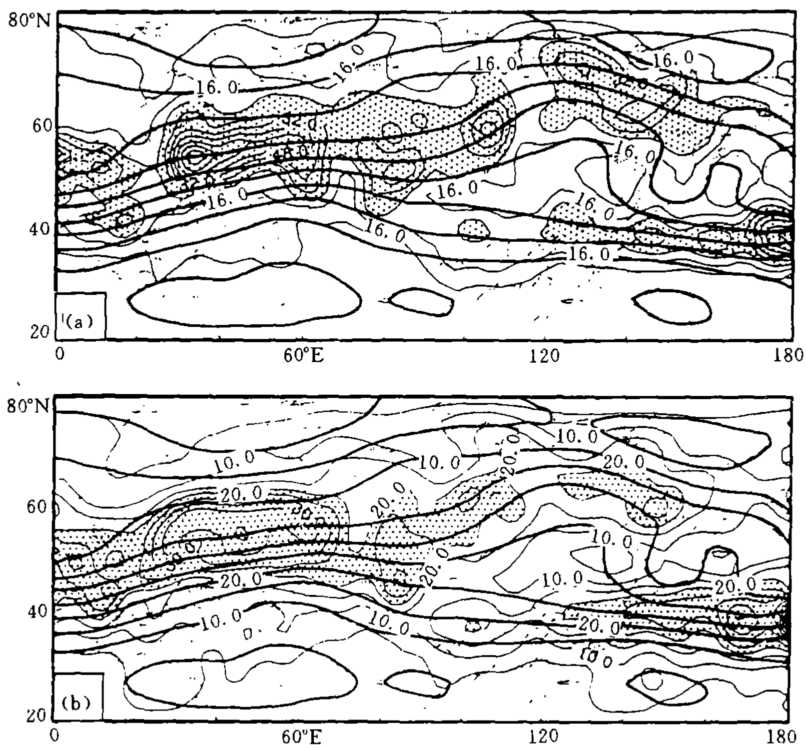

Fig. 4. Disposition of the time mean 300 hPa geopotential height (heavy solid curve, interval in 80 gpm). (a) Eddy potential vorticity enstrophy, light solid curve, interval in $8 \times 10^{-11} s^{-2}$, shading area indicates greater than 24 $\times 10^{-11}\ s^{-2}$; (b) Eddy kinetic energy, light solid curve, interval in 5 $m^2\ s^{-2}$, shading area indicates greater than 20 $m^2\ s^{-2}$ for the period July 7—15, 1980.

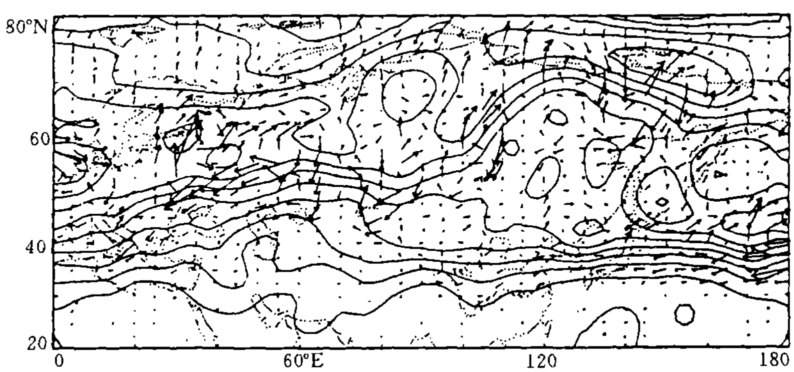

Fig. 5. Disposition of the time mean 300 hPa potential vorticity $\bar{q}$ (contour interval in $2 \times 10^{-5}\ s^{-1}$) and residual flux of eddy potential vorticity $(\overline{\bar{v}'q'})_*$ (vector) for the period of July 7—15, 1980.

respectively. It is, then, clear that the term $(\overline{\mathbf{V}'q'} \cdot \nabla\ \bar{q})$ in Eq.(11a) implies enstrophy conversion from perturbation to time–mean flow. Since the time–mean flow is dominated by larger scale systems, especially by blocking, if we use subscript " l" to denote large scale quantities, then

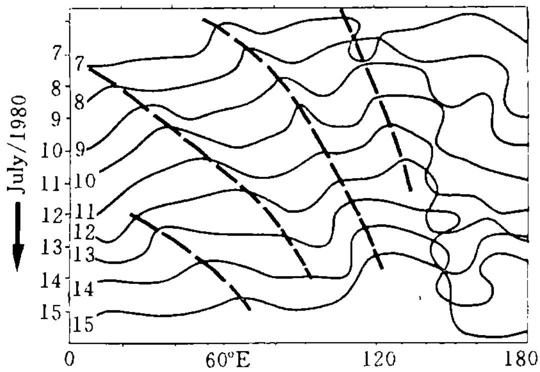

Fig. 6. Evolution of the 300 hPa 9360 gpm contour at 50°N during the period of July 7—15, 1980. Heavy dashed curve indicates ridge.

the conversion of E_e to larger scale system can be expressed by

$$\frac{dE_l}{dt} = \overline{\mathbf{V}'q'} \cdot \nabla \overline{q} = C(E_e - E_l). \tag{12}$$

Further, divide the perturbation enstrophy E_e into two parts representing for middle and small scale systems, denoted by subscripts "m" and "s", respectively, i.e.,

$$\frac{dE_e}{dt} = \frac{dE_m}{dt} + \frac{dE_s}{dt}. \tag{13}$$

Thus, Eqs.(11a) can be simplified to

$$\frac{dE_s}{dt} + \frac{dE_m}{dt} + \frac{dE_l}{dt} = 0. \tag{14}$$

Fjortoft (1953) has proved that, in a non–divergent barotropic atmosphere, energy conversion can take place only when, at least, three different scale waves are involved. Wu (1995) further proved that in a baroclinic atmosphere with divergence, such principle of multi–scale involvement for energy conversion still holds. He also found that for a weak divergent and equivalent barotropic atmosphere, energy conversion subjects to bi–directional cascade: the decrease (increase) in energy of a middle scale system must be compensated by the concurrent increase (decrease) in energy of both larger and smaller scale systems. The magnitudes of energy change satisfy the following relation:

$$\frac{dE_l}{dE_s} \simeq \frac{L_m^2 / L_s^2 - 1}{1 - L_m^2 / L_l^2}, \tag{15}$$

where "L" represents wave length.

The daily evolution of the 9360 gpm contour around 50°N at 300 hPa in the period of July 7—15, 1980 is shown in Fig. 6. During this period, the synoptic systems propagating eastward along the baroclinic zone from Europe possessed a similar feature: their horizontal scales were reduced noticeably. The scales of the three eastward propagating synoptic troughs were all halved when they approached the Lake Baikal. Downscale cascade of the energy thus occurred. According to the above mentioned principle of bi–directional energy cascade, more energy

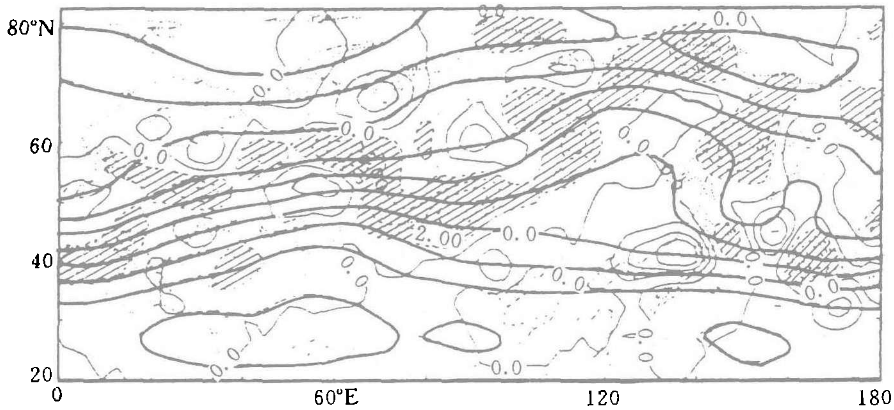

Fig. 7. Distribution of kinetic energy conversion from time mean $(\overline{K})$ to transient $(K_e)(C(\overline{K}\rightarrow K_e))$ at 300 hPa during the period July 7—15, 1980. Heavy solid line denotes mean contour. Light solid and dashed lines indicate positive and negative contours, respectively. Contour interval is 1×10^{-4} m^2 s^{-3}. Shading area indicates the region where C is less than -1×10^{-4} m^2 s^{-3}.

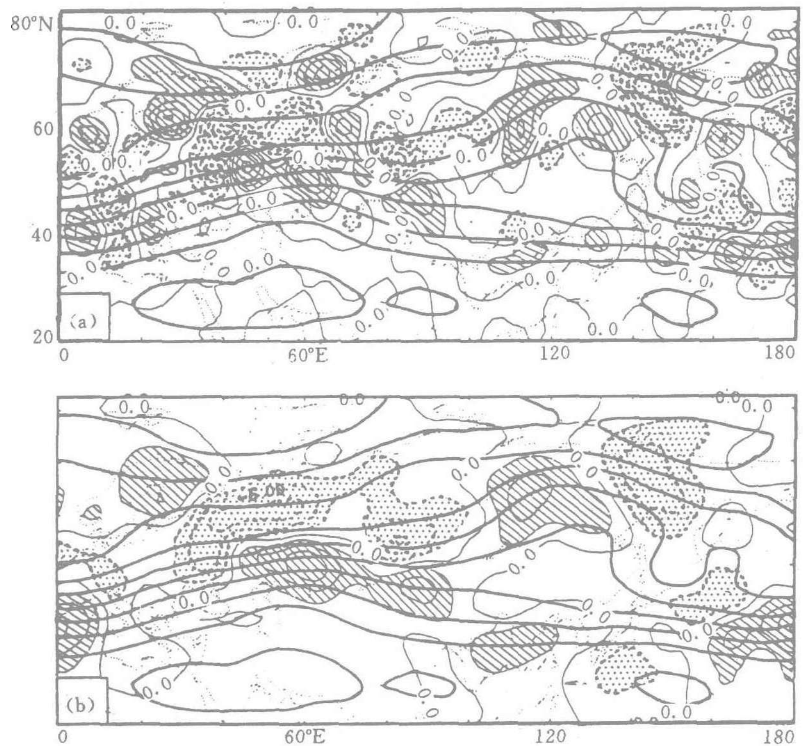

Fig. 8. (a) Distribution of mean divergence D of transient eddy flux of eddy potential vorticity. Interval in 3×10^{-11} s^{-2}. Italic and dotted shading areas indicate respectively the regions greater than 3×10^{-11} s^{-2}and less than -3×10^{-11} s^{-2}. Heavy solid line is the time mean contour. (b) Distribution of local change of time mean stream function $(\partial\overline{\psi}/\partial t)$ calculated from (a). Interval is 3 m^2 s^{-2}. Italic and dotted shading areas indicate respectively the regions greater than 3 m^2 s^{-2} and less than -3 m^2 s^{-2}. Heavy solid line is the time mean contour.

should be converted into larger scale systems. We can see from Figs. 3 and 6 that, before July 9, there existed only a weak ridge over Northeast Asia. As the synoptic systems moved towards the ridge one after another, the ridge became intensified, and its size became larger. A blocking high started to form there on July 13.

The scale of the time–mean blocking is about twice as large as that of the original synoptic systems. According to Eq.(15), about 80% of the energy of the synoptic system should be converted into the time–mean blocking system. To verify the energy conversion between the synoptic and the blocking systems, we employ the following equations

$$\begin{cases} \dfrac{\mathrm{d}\overline{K}}{\mathrm{d}t} = -C(\overline{K}\rightarrow K_e + \text{other terms}, \\ \dfrac{\mathrm{d}K_e}{\mathrm{d}t} = C(\overline{K}\rightarrow K_e) + \text{other terms}, \end{cases} \tag{16}$$

and

$$C(\overline{K}\rightarrow K_e) = \frac{\overline{u'v'}}{a}\left[\cos\varphi\frac{\partial}{\partial\varphi}\left(\frac{\overline{u}}{\cos\varphi} + \frac{1}{\cos\varphi}\frac{\partial\overline{v}}{\partial\lambda}\right)\right] - \frac{1}{a}\left[\overline{(v')^2} - \overline{(u')^2}\right]\left[\frac{1}{\cos\varphi}\frac{\partial\overline{u}}{\partial\lambda} - \mathrm{tg}\varphi\cdot\overline{v}\right], \tag{17}$$

to calculate the spatial distribution of the conversion $C(\overline{K}\rightarrow K_e)$ from (larger scale) time–mean to transient perturbation kinetic energy. The results are shown in Fig. 7. Along the diffluence flow and within the main part of the blocking, there does exist kinetic energy conversion from the synoptic eddies to the blocking system, and this is in consistent with the earlier estimation based on Eq.(15). In fact, if we inspect Fig. 3 carefully, we may find that perturbations along the diffluence flow and around the northern rim of the blocking possess "banana" shape structure. According to the theory of Zeng (1983), the energy of such perturbations will be absorbed by the mean flow, which is in agreement with our calculation.

VI. EDDY TRANSFER OF POTENTIAL VORTICITY AND MAINTENANCE OF WESTERLY JET STREAM AND FORMATION OF BLOCKING HIGH

By using the definition of material differentiation and neglecting source or sink, the time–mean potential vorticity equation (Ye et al. 1962) can be written as

$$\begin{cases} \dfrac{\mathrm{d}\overline{q}}{\mathrm{d}t} = -D, \\ D = \nabla\cdot\overline{\mathbf{V}'q'}. \end{cases} \tag{18}$$

This implies that when a parcel passes a region where eddy potential vorticity flux is diverged (converged), its anticyclonic (cyclonic) potential vorticity will increase. The distribution of D calculated based on daily data is shown in Fig. 8a. From this we see that:

(1) East of the strongest centre of the eddy enstrophy over Europe, D is positive along and to the south of the axis of the strong westerly jet and diffluence flow and negative to its north. Therefore, a parcel moving with the mean flow in the south of the axis will obtain negative potential vorticity, while that in its north will pick up positive potential vorticity. The time mean westerly jet is thus maintained and intensified due to the eddy forcing.

(2) Over the ridge and to its west, D is positive. A parcel moving with the mean flow and passing through the western part and the ridge will obtain anticyclonic potential vorticity, so

that the blocking can be maintained and intensified. Pierrihumbert (1984) has proved that along the downstream of a strong baroclinic site, blocking can develop due to eddy transfer processes. Our results are in agreement with his conclusion. It is worth mentioning that the intensity of D near the ridge is as strong as 0.8×10^{-5} s^{-1} d^{-1}, which is about 60% greater than the strong D centre (0.5×10^{-5} s^{-1} d^{-1}, Green 1977) of the famous European blocking high occurred in the summer of 1976. Assuming that the potential vorticity of a blocking high can be as strong as -2×10^{-5} s^{-1}, then such a D forcing due to eddy transfer of eddy potential vorticity may excite the blocking in 3—4 days.

Eq.(18) can be rewritten into

$$\frac{\mathrm{d}}{\mathrm{d}t}(\nabla^2-\gamma^2)\overline{\psi}=-D. \tag{19}$$

We then have

$$\frac{\partial\overline{\psi}}{\partial t}=(\nabla^2-\gamma^2)^{-1}(-D)+\text{other terms}. \tag{20}$$

Applying a reverse Helmholtz calculation to the D field shown in Fig. 8a, we can estimate the contribution of eddy forcing to the local change of mean stream function $\partial\overline{\psi}/\partial t$. The results are shown in Fig. 8b. In the area east of the region of enstrophy source over Europe, the positive height tendency forced due to eddy transfer properties appears along the jet axis and to its south, and extends northeastward and southeastward in the region east of the diffluence center. The forced negative height tendency is located to the north of the westerly jet axis. As a result, the geopotential height should increase on the south side of the jet axis, and decrease on its north, so that the geopotential gradient along the westerly jet can be maintained. In the northern part of the blocking high, the eddy forcing makes the geopotential height increase near and at the ridge, while decrease in both upstream and downstream. According to the distribution of $\partial\overline{\psi}/\partial t$ along the northern rim of the blocking (−10, +8, −8 m^2 s^{-2}), during the 8 days period the geopotential height of the ridge may increase 70—80 gpm, and that of its upstream and downstream may decrease 100 and 80 gpm, respectively. These magnitudes are close to the observed corresponding variations during the development of the blocking (refer to Fig. 3).

The analyses presented in this section then indicate that the eddy transfer of the eddy potential vorticity plays an important role in maintaining the mean westerly jet and in the formation and development of the Northeast Asian blocking high, at least in the present case.

VII. DISCUSSIONS AND CONCLUSIONS

The diagnoses in this study show that the formation, development and maintenance of the Northeast Asian blocking high occurring in the summer of 1980 are, to a great extent, associated with the continuous generation and development of mid latitude synoptic systems over Europe and West Asia. When such systems propagate eastward along the diffluence flow, their scales become smaller, and part of their energy is downscale cascaded. According to the principle of bi–directional cascade, a large part of their energy is upscale cascaded to large scale blocking high. Thus, the synoptic systems originated from the strong baroclinic zone in Europe and moving eastward play the roles of maintaining the mean westerly jet and blocking. The analyses of time mean potential vorticity also show that transient eddies can maintain the shearing vorticity of the middle Asian westerly jet and intensify the anticyclonic vorticity of the blocking. During their eastward movement, the forcing of those eddies makes the meridional difference of geopotential height across the westerly jet be maintained and the geopotential height of the blocking increased. It seams that the dynamic roles of transient eddies in forcing blocking high over Northeast Asia are very similar to those over the northern Atlantic. A slight difference between the two is that during the maintenance of the Atlantic blocking, a transient eddy forcing source is located far upstream, whereas in the development of Northeast Asian blocking, such a forcing source is more close to the blocking ridge.

Why energy cascade can occur? Shutts (1983) suggested that when a wave propagated eastward along a diffluence flow, its meridional scale be enlarged, and its longitudinal scale become smaller. In our case, the diffluence flow prior to the formation of the blocking is very weak. During its eastward propagation, both the meridional scale and the longitudinal scale of the synoptic waves decrease, showing a typical downscale cascade (ie., the general wave number increases), which is favorable for the rapid conversion from eddy energy to time mean flow. Why the scale of the synoptic system gets smaller during eastward propagation? Using baroclinic instability theory, Zhu (1987) found that over the northern flank of the large scale orography, the wavelength of the most unstable mode became shorter. In our case, the energy cascade does occur to the north flank of the Iran high and the Qinghai–Xizang Plateau, west of the Lake Baikal. It seems that the orography forcing on the northern flank of orography may be responsible for the downscale energy cascade of the synoptic systems. It can also explain the frequent occurrence of blocking high over Northeast Asia. However, the conclusion requires more studies.

In our study, we have also used baroclinic potential vorticity and non–divergent barotropic potential vorticity (absolute vorticity) to replace the potential vorticity defined in Eq. (1), then repeated the above calculation. The results were very similar to what we have shown here. It seems that baroclinic and divergent effects are secondary. However, this may be due to the fact that our analyses were focussed on the equivalent barotropic layer. At other layers, the bi–directional cascade principle may not hold (Wu 1995), and the impacts of the baroclinity and the divergence may become important. These reserve for further study. In addition, the relative importance of eddy transfer of sensible heat and potential vorticity also needs to be explored. Nevertheless, from this study, it turns out to be clear that during the formation of the blocking high over northeastern Asia in summer, the internal forcing associated with transient eddy transfer is very important. Since the stable maintenance of the blocking high over Northeast Asia is closely related to the persistent maintenance of the high ridges over the northern China, when we try to understand drought climate in northern China, we should pay attention to the evolution of weather pattern over Europe and West Asia. In our future study, we should also investigate the formation of the strong European baroclinic zone so as to improve the prediction of the persistent anomalous weather.

We would like to thank Profs. Ye Duzheng, Tao Shiyan and Zeng Qingcun for their valuable discussions during this study.

REFERENCES

Austin, J. F. (1980), The blocking of middle latitude westerly winds by planetary waves, *Quart. J. Roy. Meteor. Soc.*, **106:** 327—350.

Berggern R., Bolin. B. and Rossby, C. G. (1949), An aerological study of local motion its perturbations and break down, *Tellus*, **1:** 14—37.

Bi Moying and Ding Yihui (1993), Potential vorticity analysis of the blocking situation during the northern China drought in the summer of 1980, *J. Appl. Meteor.*, **3:** 145—156 (in Chinese).

Blackmon, M. L. (1976), A climatological spectral study of the 500 hPa geopotential height of the Northern Hemisphere, *J. Atmos. Sci.*, **33:** 1607—1723.

Chen Delin and Xu Xialu (1980), Drought in north and flood in south, *Meteor. Monthly*, **10:** 36—38 (in Chinese).

Dong Liqing and Xu Xialu (1980), Persistent flood in south, and persistent drought in north, *Meteor. Monthly*, **11:** 37—39 (in Chinese).

Fjortoft, R. (1953), On the changes in the spectral distribution of kinetic energy for two dimensional, non-divergent flow, *Tellus*, **5:** 225—230.

Green, J. S. A. (1977), The weather during July 1976: some dynamical consideration of the drought, *Weather*, **32:** 120—126.

Gu Zhencao, Qu Zang and Cao Jiping (1957), Experiment study of numerical weather prediction using a 3-layer quasi-geostrophic model, *Acta Meteor. Sinica*, **28:** 141—156 (in Chinese).

Illari, L. (1984), Diagnostic study of the potential vorticity in a warm blocking anticyclone, *J. Atmos. Sci.*, **41:** 3518—3526.

Jiao Peijing and Wang Yongxiang (1980), High temperature in Northeast and South China, torrential rain in the reaches of the Huanghe, Huaihe, and Changjiang Revers, *Meteor. Monthly*, **9:** 37—39 (in Chinese).

Namias, J. (1964), Seasonal persistence and recurrence of European blocking during 1958—1960, *Tellus*, **16:** 394—407.

Pierrehumbert, R. T. (1984), Local and global baroclinic instability of zonally varying flow, *J. Atmos. Sci.*, **41:** 2141—3162.

Shutts, G. J. (1983), The propagation of eddies in diffluent jet streams: eddy vorticity of blocking flow fields, *Quart. J. Roy. Meteor. Soc.*, **109:** 737—761.

Wu Guoxiong (1995), Single and bi-directional energy cascade in the atmosphere, *Chinese J. Atmos. Sci.* ,**19:** 52—62.

Wu Guoxiong and Zou Xiaolei (1990), Progress in the research of dynamics of persistent anomalous weather, *Progress in the Study of Flooding and Drought*, Ed. by Ye Duzheng, China Meteor. Press, Beijing, pp.71—77 (in Chinese).

Ye Duzheng, Tao shiyan, Zhu Baozhen, Yang Jianchu, and Chen Longxun (1964), *Study on the Winter Blocking Situation in the Northern Hemisphere*, Science Press, Beijing (in Chinese).

Zeng Qingcun (1983), The evolution of a Rossby-wave packet in a three-dimensional baroclinic atmosphere. *J. Atmos. Sci.*, **40:** 73—84.

Zhu Baozhen (1987), Regional circulation anomaly characteristics over eastern Asia in relation to the boundary forcing, *The Climate of China and Global Climate*, Ed. by Ye Duzheng et al. , Chinese Ocean Press, Beijing, Springer-Verlag, pp.259—269.