The Maintenance of the Blocking over the Ural Mountains during the Second Meiyu Period in the Summer of 1998①

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(Received November 10, 1999; revised June August 29, 2000)

ABSTRACT

The 1998 summer–time floods at the Yangtze River basin of China, the severest in last 50 years or so, directly resulted from the abnormal extension of Meiyu (rainy season), which was related to a weak East Asian summer monsoon and persistent anomalies of extratropical circulation. The long persistence of blocking over the Ural Mountains is a conspicuous feature. The physical processes responsible for the prolonged maintenance of this key system are investigated in terms of internal forcing (transient eddy upon basic flow) and external forcing (tropical heating forcing) via diagnosis and numerical experiments in the paper.

Using the adjoint method, the location and structure of optimal perturbations favorable for the development and maintenance of Ural blocking are identified, which shows an apparent coincidence with the observed storm track at the eastern Atlantic to Europe sector. The diagnosis of E–vector and the response of baroclinic stationary wave to transient forcing both suggest further that the enhanced transient eddy activity favors the occurrence and maintenance of positive anomalies.

The upper–level jet and heat sources (sinks) during that period are calculated, and the results indicate that the anomaly of upper jet and tropical heating is evident. The ensemble forecasting experiments by a GCM, IAP T42L9 show that the anomalous heating over the tropics, especially over the central–western Pacific and Atlantic, favors the formation of positive anomalies of height at the Ural region. Finally, a self–sustain mechanism of positive anomalies through two–way interaction between planetary stationary wave and transient eddy under the stimulation of anomalous tropical heating is proposed.

Key words: 1998 floods in China, Blocking high over the Ural Mountains, Tropical abnormal heating, Transient eddy, Two–way interaction

1. Introduction

The 1998 floods at the Yangtze River basin in China are the second severest in the 20th century next to 1954. Its direct and primary cause is the anomalous extension of Meiyu (rainy season) (Tao et al., 1998; Huang et al., 1998), which, in turn, is closely associated with anomalous circulation. There existed three anomalous aspects of atmospheric circulation over East Asia (Yan, 1998): (1) ITCZ is weaker than normal, and thus there are less tropical storms over the tropical western Pacific; (2) blocking patterns emerge frequently at middle and high latitudes, especially over the Ural Mountains and the Okhotsk Sea; (3) the subtropical high

①This work was supported by the CAS Key project KZCX2–203 the Research Program for the Excellent State Key Laboratory (Grant No.49823002), and the Study on Formation Mechanism of Key Weather Disaster in China (Grant No. 97–13G–21).

over the western Pacific (hereafter, SHWP) is weaker and situated in a position south of the normal. So the anomalous lasting of the blocking high over the Ural Mountains is an important aspect of circulation pattern, as was also found by other researchers (Bi, 1998; Yang, 1998). There have been less studies on summer–time Ural blocking so far in comparison with those over Northeast Asia, especially over the Okhotsk Sea, which is associated with abnormal Meiyu more closely. But the twin blocking pattern with one over the Ural Mountains and the other over the northeastern Asia is an important pattern resulting in Meiyu, especially during the middle and later phases (Zhu et al., 1982). The floods at the Yangtze River basin are usually related to the prolonged Meiyu period, therefore it is essential to study the formation and maintenance of Ural blocking, in particular, those of prolonged persistence.

There are many theories on the formation and maintenance of blocking, among which the forcing from synoptic–scale transient eddy (internal forcing) upstream and that of heating source (external forcing) are widely cited (Shutts, 1983; Shukla and Wallace, 1983). Liu and Wu (1996) studied the maintenance of the blockings over the North Pacific, the North Atlantic Ocean and Alaska individually, and found that the relative importance of transient eddy is different. Nakamura et al. (1997) compared the roles of transient eddy and low–frequency wave in the blockings over Europe and the Atlantic individually, and pointed out that the quasi–stationary wave train plays a more important role than transient eddy in the blocking over Europe, while it is contrary over the Pacific. The low–frequency wave is related to external forcing, especially the tropical heat sources. Lu and Huang (1996) conducted numerical experiments to study the impact of the SSTA over the tropical western Pacific upon the blockings over the northeastern Asia, and pointed out that the negative SSTA is in favour of the maintenance of the blocking. Tropical heating can also influence blocking through the Hadley circulation, upper jet and transient eddy indirectly.

The strongest ENSO event in the last century occurred in 1997 / 98, which reached its peak in December 1997 and began to retreat from May 1998. There was a band of cold water along the equator near the dateline in June. It is under the background of ENSO event that the floods occurred. Some studies (e.g. Tao et al., 1998; Huang et al., 1998; Yan, 1998, etc.) suggest that the abnormal precipitation in summer over the Yangtze River basin does not response to ENSO as directly as that over the areas such as South America, North African and Indian monsoon areas, but is related to the evolution of events. And the floods are likely in the following, rather than the current, year of an ENSO event. However the physical mechanism underlying remains unclear.

The long maintenance of the blocking over the Ural Mountains is studied in terms of two aspects, namely internal and external forcing, especially tropical heating. This paper is written in five sections. In Section 2 the persistent anomaly of circulation over the Ural Mountains is defined, and its connection with abnormal Meiyu is investigated. In Section 3 the long maintenance of the blocking over the Ural Mountains is diagnosed, and the roles of transient eddy and tropical anomalous heating are explored. Section 4 is the numerical experiments, in which the contribution to the blocking from the synoptic–scale transient eddy is estimated by a baroclinic linear stationary wave model (Ting and Held, 1990), and that from abnormal heating over different tropical areas is studied through ensemble experiment of a global GCM, IAP T42L9. The last section contains a summary and discussion.

The data set used here includes NCAR / NCEP reanalysis from 1980 to 1997 for grids of 2.5 by 2.5 longitude–latitude degrees. And for the 1998 data, NCEP analysis was used instead for lack of NCAR / NCEP reanalysis in 1998, which has been interpolated into the same grids. All data include 12 vertical levels of 1000, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70, 50 hPa.

2. The floods in China in the 1998 summer and the blocking over the Ural Mountains

Here blocking is studied in terms of the persistent anomaly, the threshold of which can be seen in Li and Ji (2000), and will be introduced briefly below. First we choose a key point to represent an interesting area, then calculate the departure of geopotential height from the seasonal trend at 500 hPa, and normalize it by the zonal–average standard variance. The seasonal trend is fitted by the daily climate with the least quadric method as Dole and Gordon (1983) (DG83 hereafter). If the normalized anomaly at the key point is greater than 0.9 (less than −0.9) and persists for more than 10 days, then a case of positive (negative) persistent anomaly can be defined. The height has been filtered by 5–day–running mean in order to remove the impact upon the case definition by the synoptic–scale transient eddy. According to this threshold, the global distribution of persistent anomaly case is calculated in the boreal winter and summer from 1980 to 1997, and the results over the extratropics in winter / summer are in agreement with DG83, and Li and Ji (1994), respectively. Although the definition is just a modification of DG83, it is suitable for global analysis but the latter suitable only for the extratropics.

We choose (60°E, 60°N) as the key point of the region over the Ural Mountains. The threshold 0.9 of normalized anomaly corresponds to different height anomaly at different latitudes, and is equivalent to about 82 gpm over the Ural Mountains (Li and Ji, 2000). By this threshold the cases in the 1998 summer can be identified. The results show that there is a persistent positive anomaly case (blocking) with the duration of 19 days from 17 July to 4 August, and a negative one with the duration of 11 days from 25 June to 5 July respectively. The another positive one lasts only 8 days from 11 to 18 June, and does not meet the persistence threshold of 10 days, thus is not included. The first positive case is the longest in last 20 years or so (Li and Ji, 2000). Comparing with the Meiyu period (Tao et al., 1998), we can see that the period of positive anomalies (blocking) corresponds to the second stage of the Meiyu, and the negative to the intermittence between the two stages. The second stage of Meiyu plays a direct role in the formation of severe floods. We will focus on the Ural blocking in the following.

Figure 1 is the composite height and anomaly at 500 hPa during the blocking period. One can see a strong blocking high over the Ural Mountains, and the "twin blocking" pattern over Eurasia, with the other blocking over the eastern Siberia and a deep trough over the Lake Baikal. Correspondingly there are positive centers with maximum departure of 14 dam over the Ural Mountains and 10 dam over the eastern Siberia respectively (Fig. 1b). Negative anomalies extending from North China and the middle reaches of the Yangtze River to the southern Japan indicate that SHWP is weaker than normal. Under the background of this stable flow pattern, the confluence of cold and dry air from the north with warm and moist flow along the northwestern flank of SHWP dominates the Yangtze River basin, thus leading to the recurrence of Meiyu. This suggests that the long persistence of the Ural blocking is closely related to the recurrence of Meiyu, i.e. the prolonged rainy season, and thus is one of the key contributor to the floods.

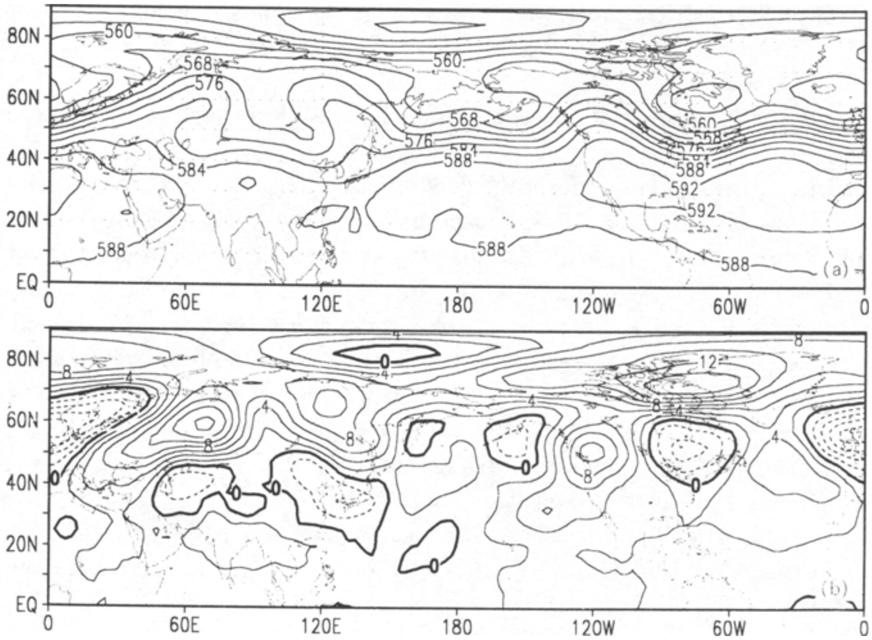

Fig. 1. Composite height and anomalies at 500 hPa from 17 July to 4 August in 1998 Unit: dam. (a) height (b) height anomaly to climate.

3. Diagnosis on the maintenance of Ural blocking

To shed some light on the long persistence of the Ural blocking, two factors have been investigated: the internal forcing by the transient eddy and the external forcing by the tropical anomalous diabatic heating.

3.1 *The contribution from synoptic–scale transients –adjoint optimal sensitivity perturbation (OSP) and E–vector analysis*

The contribution from transient forcing is well acknowledged. However, the favorable transient cannot be arbitrary. One may ask: given a target area, where and what kind of structure a perturbation is that contributes most to a specific weather system in that area. This perturbation is called optimal sensitivity perturbation (OSP hereafter), and can be calculated by the adjoint technique in a linear framework, given a slow–varying basic flow in finite time (Yang et al., 1998a). Yang et al. put forward the concept of OSP and used this technique to make a comparative analysis for 1991 floods and 1985 drought in the Yangtze and Huaihe River basin. For our case, the target will be the blocking (negative vorticity) over the Ural Mountains area.

The OSP under the basic flow of the 1998 blocking period is calculated with the model as Yang et al. (1998a). From Fig. 2a one can see that the OSP favoring the development of blocking over the Ural Mountains in 4 days is mainly situated over the areas: (1) negative vorticity area from the Arabia to the eastern North Atlantic with the center over the Mediterranean Sea, (2) positive vorticity area from the central Asia and Caspian Sea to the

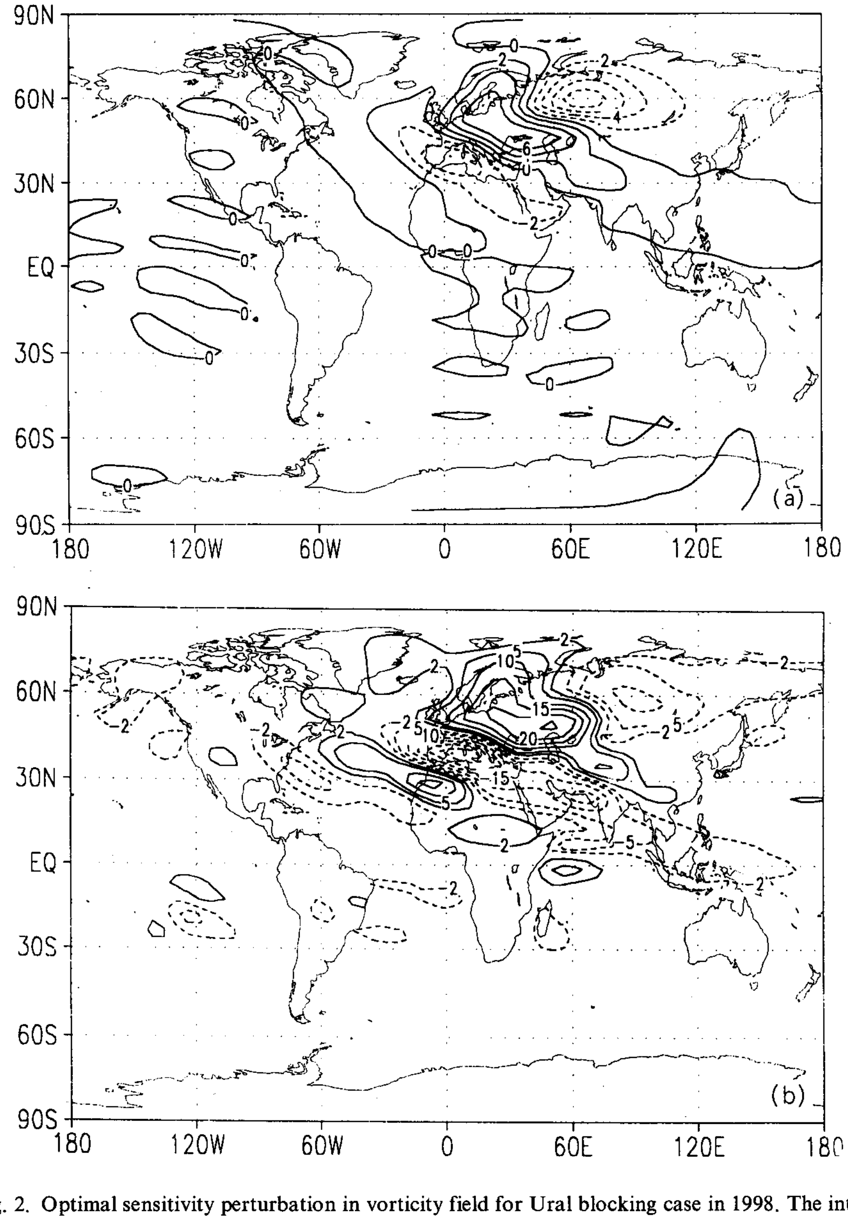

Fig. 2. Optimal sensitivity perturbation in vorticity field for Ural blocking case in 1998. The interval of contour 2×10^{-5} 1 / s and the magnitude have only relative meaning. (a) t = 4d; (b) t = 8d.

northern Europe, (3) negative vorticity area from Ural eastward to the Lake Baikal. One can see that the first two of the OSP are in NW–SE orientation, and a perturbation to the south of a jet with this kind of orientation, i.e. a leading structure, is apt to extract energy from basic flow and develop. Figure 2b shows the OSP for the finite time of 8 days. As expected, the basic feature is similar to Fig. 2a, except for a slight phase shift and the train of centers with alternate signs extending further southwest. Besides, the OSP centered at the Mediterranean Sea stretches southeastward with another center appearing at the Bay of Bengal. Initial perturbations with major projection on these OSP will favor the development of Ural blocking in 8 days.

In order to investigate the connection between the transient eddy activity and the optimal sensitivity perturbation during this period, we have calculated the observed synoptic–scale eddy distribution, and compared with the climatological mean of the same period. Here we adopt the mean variance of synoptic–scale eddy height to represent the strength of transient eddy activity using a 31 points filter (Sun, 1992). In Fig. 3, it is shown that the eddy activity is more frequent than the climate over the northern Pacific and Atlantic, especially from the central North Atlantic to the western Europe around the point (20°E, 60°N). In comparison with Fig. 2, one can see that the intensified eddy activity center is just situated in one of the optimal sensitivity perturbation centers, which suggests that the anomalous synoptic–scale perturbations favor the maintenance of the Ural blocking. Whether this coincidence is just an incident or there is some mechanism behind to lead the two into a consistent manner is an interesting problem to be further studied.

In order to investigate further the role of synoptic scale eddy in the maintenance of the

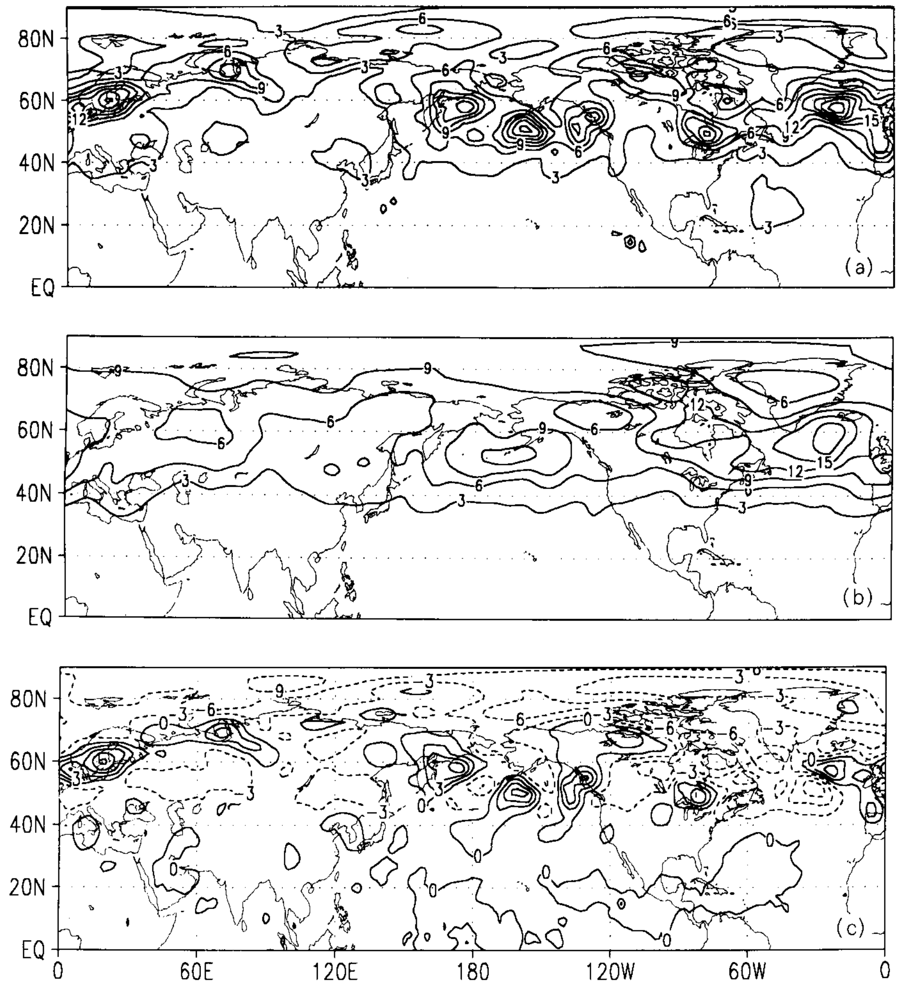

Fig. 3. Synoptic scale transient eddies distribution during Ural blocking and its comparison to the climate mean. (a) 17 July to 4 August 1998; (b) climate mean from 17 July to 4 August; (c) (a)–(b). Unit: 10^2 m^2.

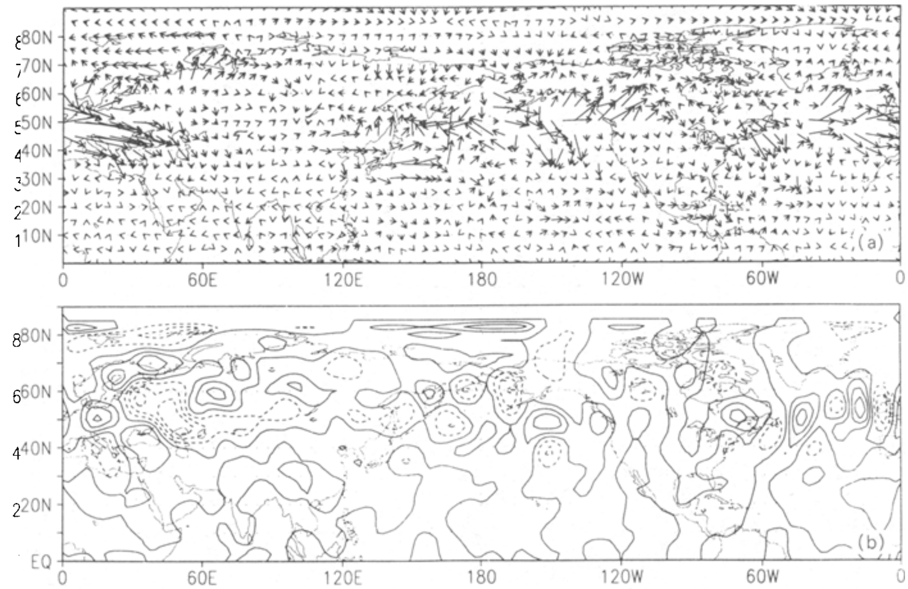

Fig. 4. Mean synoptic–scale eddies E–vector (a) from 17 July to 4 August and its divergence (b). In (a) the length of E–vector at the point (60°E, 70°N) represents 8.95 $m^2 s^{-2}$, in (b) the interval is 10^{-5} m s^{-2}.

Ural blocking, E–vector of synoptic–scale eddy and its divergence are calculated (Fig. 4). The divergence of E–vector indicates the transient eddy forcing upon the time–mean basic flow, and westerlies will accelerate (decelerate) where E–vector diverges (converges) (Hoskins et al., 1983).

$$\vec{E} = (\overline{v'^2} - \overline{u'^2}, -\overline{u'v'})$$

From Fig. 4, it can be seen that there is a convergence of $\vec{E}$ over the Ural Mountains and the west flank, while divergences on the south and north, which suggest that the synoptic–scale eddies make the westerlies decelerate over the Ural Mountains and separate into two branches on the south and north individually, and thus favor the maintenance of the blocking. The maximum area of synoptic–scale eddy activity is just located upstream of E–vector convergence over the Ural Mountains, thus plays an important role in the maintenance of the blocking, which is consistent with the OSP analysis above.

3. 2 *Upper–level jet and tropical heating during the blocking period*

It is natural to ask why the synoptic–scale transient eddy activity is so frequent at the sector from the northwestern Atlantic to western Europe during the period. Since there exists interaction between the large–scale upper jet and the synoptic–scale transient eddy, and the position of maximum eddy activity is usually situated in the poleward side of upper jet exit, we will address the problem from the point that upper jet will modulate and steer transient activity.

Here the zonal wind u at 200 hPa is used to analyze the upper jet. Figure 5 shows u–wind during the period and the climatological mean of the same period is also given for

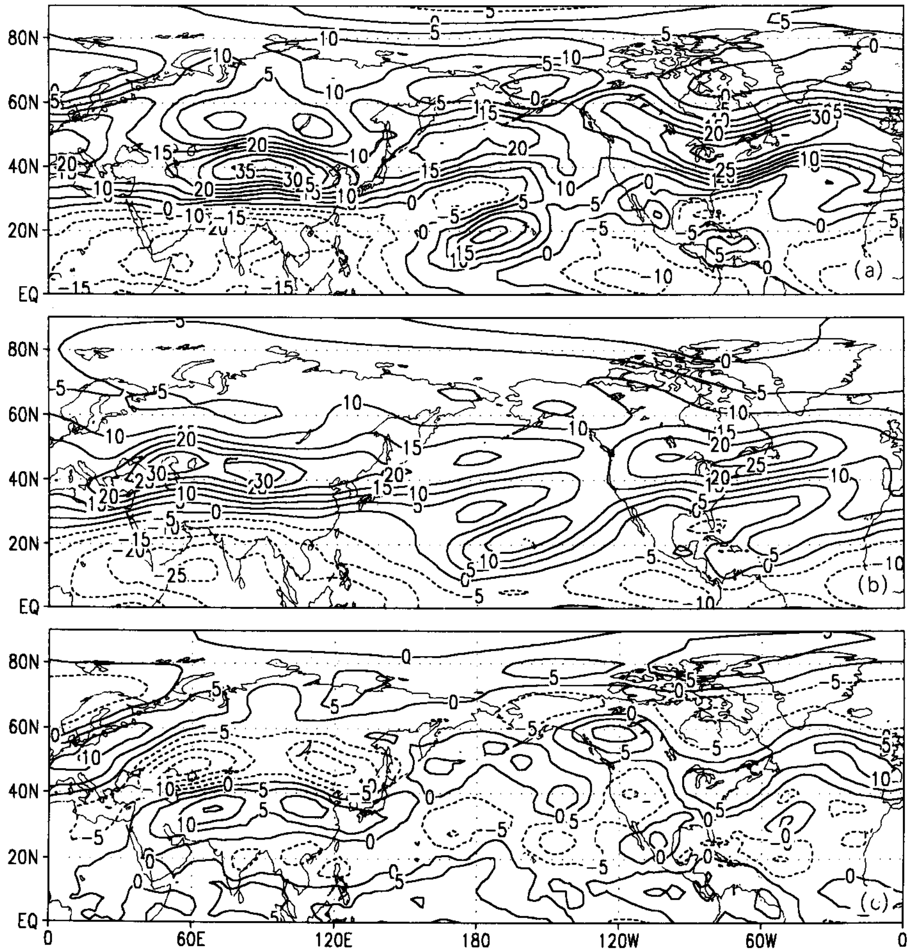

Fig. 5. Zonal wind speed at 200 hPa during 1998 case and its comparison to climate mean. Unit: m / s. (a) From 17 July to 4 August 1998; (b) climate mean from 17 July to 4 August; (c) (a)–(b).

comparison. From Fig. 5 we can see that the zonal wind is greatly different from the climate in several aspects: (1) the upper jet at mid–latitudes from Eurasia to the Pacific extends eastward and bifurcates into two branches. The eastern branch is situated over the central Pacific with the maximum speed of 20 m / s, and the western branch over the central Asia with the maximum speed over 35 m / s, greater than the climate mean of 30 m / s. (2) The mid–latitude jet from northern America to the Atlantic extends eastward with the contour 20 m / s covering from the central North Atlantic to western Europe, the maximum speed being more than 30 m / s, 5 m / s greater than the climatological mean near the jet core. The jet track is longer but narrower with easterly anomalies on the south and north of the track (Fig. 5c). (3) The easterly jets over the tropical East Pacific and Atlantic shift a bit northward. The position with the maximum synoptic–scale transient activity is just situated at the poleward side of the jet exit over North America and the Atlantic, which demonstrates that the enhancement of synoptic–scale transient activity is tied to the jet anomaly.

To go a step further, we will examine what is behind the anomalous jet during the period in the following. The formation of the large–scale upper westerly jet is related to the conversion of potential energy into kinetic energy in the frontal zone, and the local Hadley circulation has a direct influence on the frontal zone and upper jet. The vertical meridional circulation over the sector from North America to the Atlantic (120–10°W) during the case period was calculated, and the strengthening of Hadley circulation can be found (not shown) comparing with the climate, which can be seen from the strengthening of the subtropical high over the Atlantic too (see Fig. 1).

One of the factors to drive Hadley circulation is tropical heating. Mo et al. (1994) simulated the response of extratropics to SSTA in the tropics, and found that the positive SSTA will intensify the convection and hence the local Hadley circulation, and change the position and strength of upper divergence flow. Consequently, the position and strength of upper jet will change, and then the synoptic–scale eddies will be re–organized. The tropical heat sources (sinks) will also influence middle and high latitudes by the triggering of Rossby wave. The above results naturally lead us to look into the feature of tropical thermal forcing.

Figure 6 shows the distribution of apparent heat sources derived from the residual method (Yanai et al., 1973). Climate mean is calculated daily from 17 July to 4 August of 1987–1996. In Fig. 6, there are several regions with the positive heating anomaly greater than 100 W/m^2 over the tropics or subtropics of the Northern Hemisphere: (1) from the tropical East Pacific to the west of North America, central America and the tropical Atlantic, (2) from the south end of the Indian peninsula to the Arab Sea and the central East Africa, (3) from the Korea peninsula to South Japan, and the western North Pacific. There are several regions with the negative anomaly (cooling) lower than −100 W/m^2: (1) most of the area along the equator and the tropical central western Pacific (2) from Indo–China Peninsula to South China, (3) the central–west of the subtropical Atlantic. The joint effects of the positive heating anomaly from the tropical East Pacific to central America, the equatorial Atlantic and the cooling over the region of the subtropical western Atlantic will result in the strengthening of the local Hadley circulation, hence the acceleration of the upper jet over North America to the central Atlantic.

The results above show that the anomalous heating distributes over the whole tropics, but each anomalous heating center may have different contribution to the maintenance of the Ural blocking. Trenberth and Branstator (1992) used a linear primitive equation spectral model to estimate the contribution of heating at different positions to the formation of anomaly circulation resulting in 1998 drought over North America. We will conduct numerical experiments to study the contribution to the maintenance of the Ural blocking from these anomalous tropical heating centers, individually.

To look for the cause of tropical anomalous heating, it is natural to link to the SSTA. The strongest ENSO of the 20th century happened in 1997/98, and +SSTA with a maximum greater than 2.5°C over the equatorial eastern Pacific lasting till May 1998. Although −SSTA had begun to emerge over the equatorial central Pacific at the beginning of June 1998, −SSTA was mainly confined in the area (5°S–5°N, 180–120°W) till the end of July, while +SSTA remained evident over the east of 120°W, especially with +SSTA$\geqslant$+2.5°C north of 10°N (Huang et al., 1998). It can be seen that the positive/negative heating anomaly centers well correspond to the positive/negative SSTA in most tropical areas, which indicates that anomalous tropical heating during this period is related to the background of ENSO event.

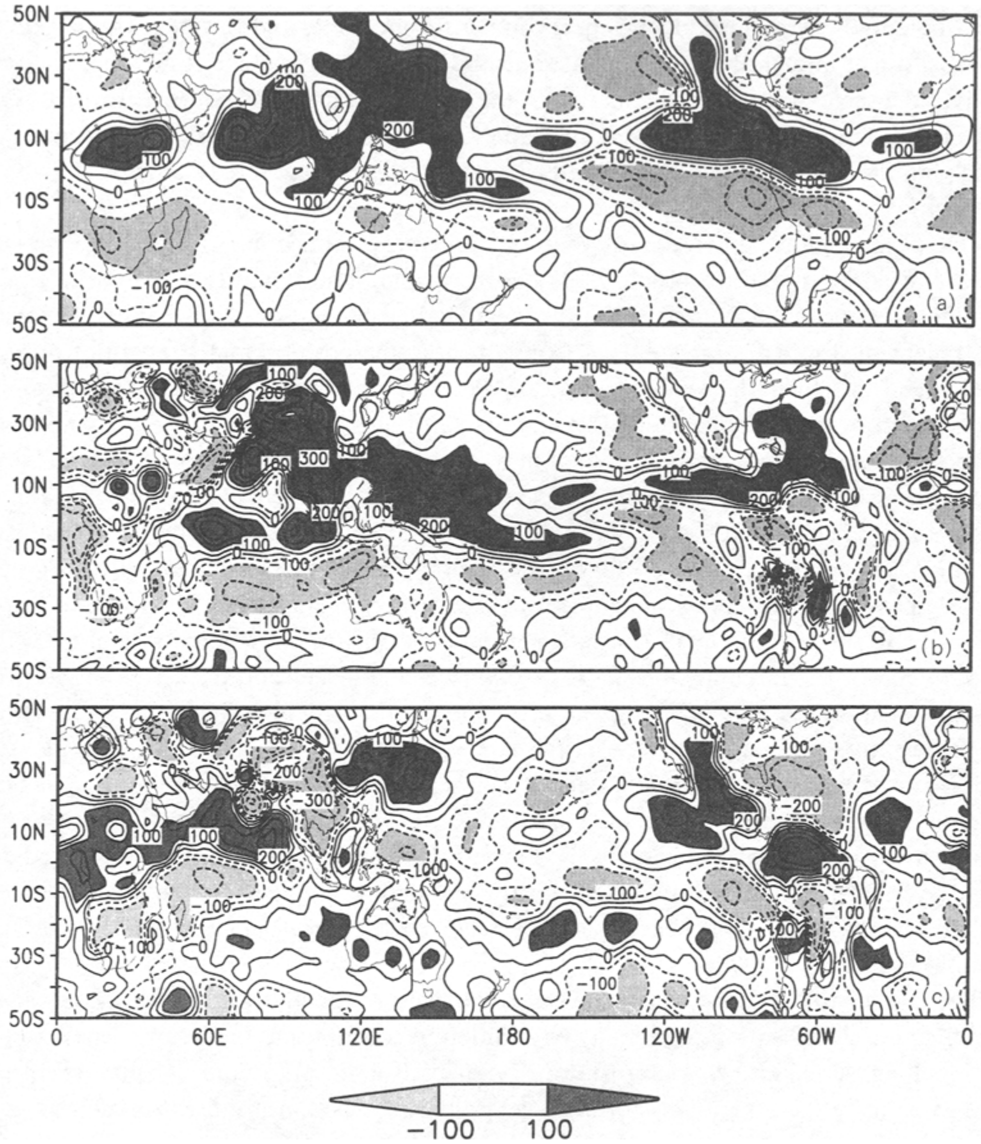

Fig. 6. Column heating during 1998 case and comparison to climate mean. (a) 17 July to 4 August in 1998; (b) climate mean from 17 July to 4 August; (c) (a)–(b). The interval of contour is 50 Wm^{-2}, but 100 when the value is greater than 100 in (c).

4. Numerical analysis

4.1 *The effect of transients*

It is difficult to estimate the contribution of transient forcing and diabatic heating by GCM because of nonlinear interaction, so we use a baroclinic linear stationary model (Ting and Held, 1990) to address this problem. The horizontal resolution of the model is rhomboidal R15, and there are nine vertical σ levels with unevenly distributed σ values

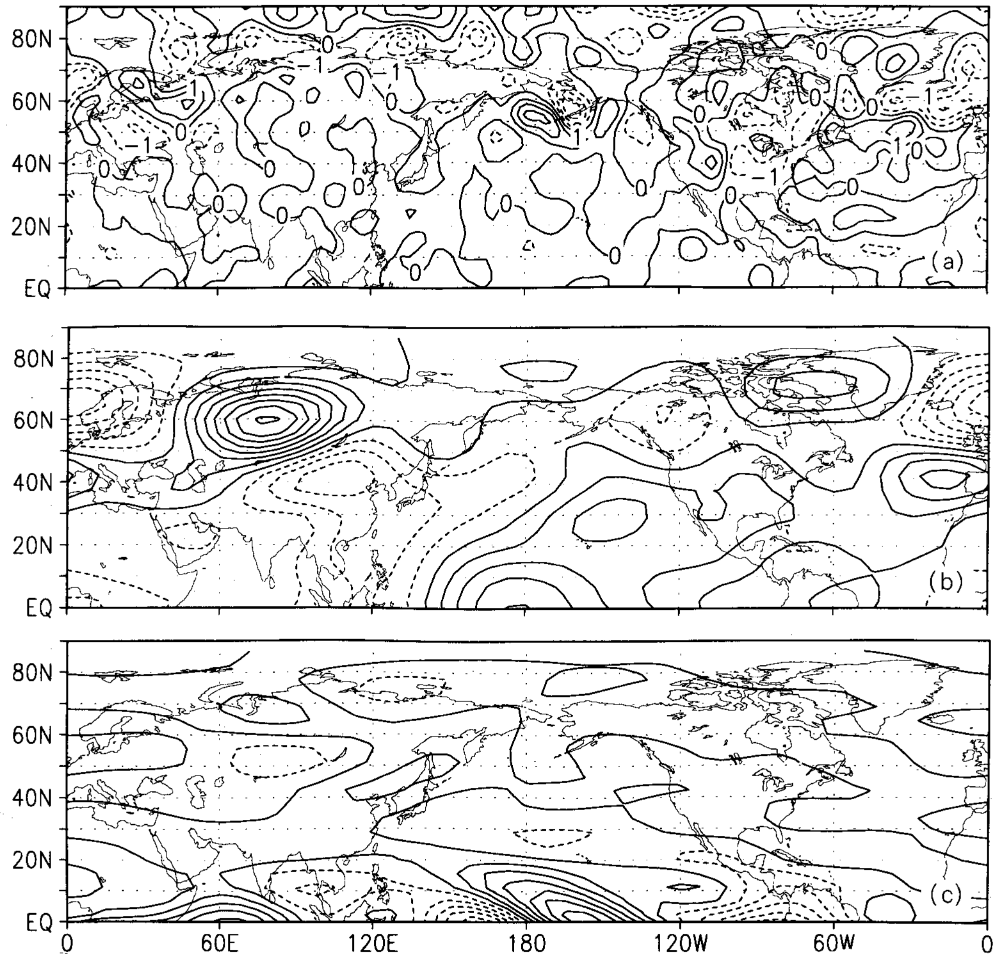

Fig. 7. (a) Thermodynamic forcing F_{Temp} at 700 hPa during the blocking period. Unit: 10^{-6} K s^{-1}. (b) The stationary response of 500 hPa height to the transient forcings. Unit: dam and the interval is 5. (c) The stationary wave response of 200 hPa zonal wind to transient forcings. Unit: m / s and the interval is 5.

(0.025, 0.095, 0.205, 0.350, 0.515, 0.680, 0.830, 0.940, 0.990). The basic state $(\zeta, D(u,v), T, \dot{\sigma}, \ln(Ps))$ is defined as the mean during the case period and can be calculated by NCEP daily analysis. The forcing terms in the model include the diabatic and the transient forcing. Dissipative terms include Rayleigh friction, Newtonian damping, and biharmonic diffusion in the vorticity, divergence, and thermodynamic equations. Here transient forcing is calculated of synoptic scales, and they can be expressed as follows in the pressure coordinate.

$$F_{\text{vor}} = -\nabla \cdot (\overline{V'_h \zeta'}) ,$$

$$F_{\text{Div}} = -k \cdot \nabla \times (\overline{V'_h \zeta'}) - \frac{1}{2} \nabla^2 \cdot \overline{V'^2_h} ,$$

$$F_{\text{Temp}} = -\left(\frac{p}{p_0}\right)^{R/C_p} \left(\nabla \cdot (\overline{V'_h \theta'}) + \frac{\partial (\overline{\omega' \theta'})}{\partial p} \right) .$$

To shed light on the strength of transient forcing, Fig. 7a displays the distribution of transient thermodynamic forcing F_{Temp} at 700 hPa. Figures 7b, c are the responses of 500 hPa height and zonal wind at 200 hPa of stationary wave respectively. The maximum response of height is situated at the Ural Mountains, which illustrates the contribution of the transient forcing to the positive height anomaly at 500 hPa, or to the maintenance of Ural blocking. From Fig. 7c, it can be seen that transient forcing is in favor of the weakening of zonal wind at 200 hPa at the Ural Mountains and intensification over the area south and north to of the Ural Mountains respectively, thus favorable for Ural blocking. These results of the linear stationary wave are in agreement with the diagnosis above.

4. 2 *The effect of abnormal tropical heating*

We conduct ensemble integration experiments with 5 members to investigate the contribution of tropical anomalous heating to the maintenance of blocking. The model adopted here is IAP T42L9, a global spectral model developed by Ji et al. (Ji et al., 1990; Zhang et al., 1995). Its dynamic frame is formed by introducing hydrostatic extraction on the basis of ECMWF version with triangle truncated wave number 42 in horizontal, and 9 levels in the vertical using the terrain–following sigma coordinate ($\sigma = p / p_s$). The main physical processes include radiation, vertical turbulent transfer, surface process, large–scale condensation and cumulus convection, horizontal diffusion, subgrid–scale gravity wave drag, etc. Zhang et al. (1995) also conducted a series of forecasting experiments, and showed that the model has good performance, and can forecast some complex synoptic processes such as the termination of Meiyu, the northward shift of the subtropical high, and the evolution of some tropical storms well.

Here total 6 sets of experiments with 5 members in each of them are carried out, and the specification is described as follows.

Experiment 1, i.e. control run (denoted as CLI_ht): the diabatic physical processes of the model are turned off, and model heating is replaced by climate mean heating over the tropics (30°S–30°N) during the blocking period and remains constant in the integration.

Experiment 2 (denoted as 98HT): as CLI_ht but model heating over the tropics is replaced by the mean heating during the period.

Experiment 3 (denoted as 98HT_EP): as 98HT but only the heating over the East Pacific (135–80°W, 0°–30°N) replaced.

Experiment 4 (denoted as 98HT_INAF): as 98HT but only the positive heating over the tropical Indian Ocean and North Africa (0°–100°E, 15°S–30°N) replaced.

Experiment 5 (denoted as 98HT_WCP): as 98HT but only the heating over the tropical central and West Pacific (90–135°W, 15°S–30°N) replaced.

Experiment 6 (denoted as 98HT_ AA): as 98HT but only the heating over the mid–America and the tropical Atlantic (130°W–0°, 15°S–30°N) replaced.

The regions with changed heating above are showed in Fig. 8a. The NCEP analysis of 1200UTC 14, 15, 16 July and 0000UTC 15, 16 July, 1998 are used as initial fields of each ensemble experiment, and the integration time is 15 days. We use the ensemble mean of integration valid for 20–29 July. Here two factors have been considered: (1) integration within the spin–up time of the model is removed; (2) all experiments are on extended–range scale, and there will be greater errors with longer integration time. Figures 8b, c display the evolution of global root mean square (RMS) vorticity, total kinetic and potential energy for the experiment CLI_ht, 98HT respectively, both of which have the same initial field of 1200 UTC, 14 July. It can be seen that these statistical variables approach a steady state after the integration

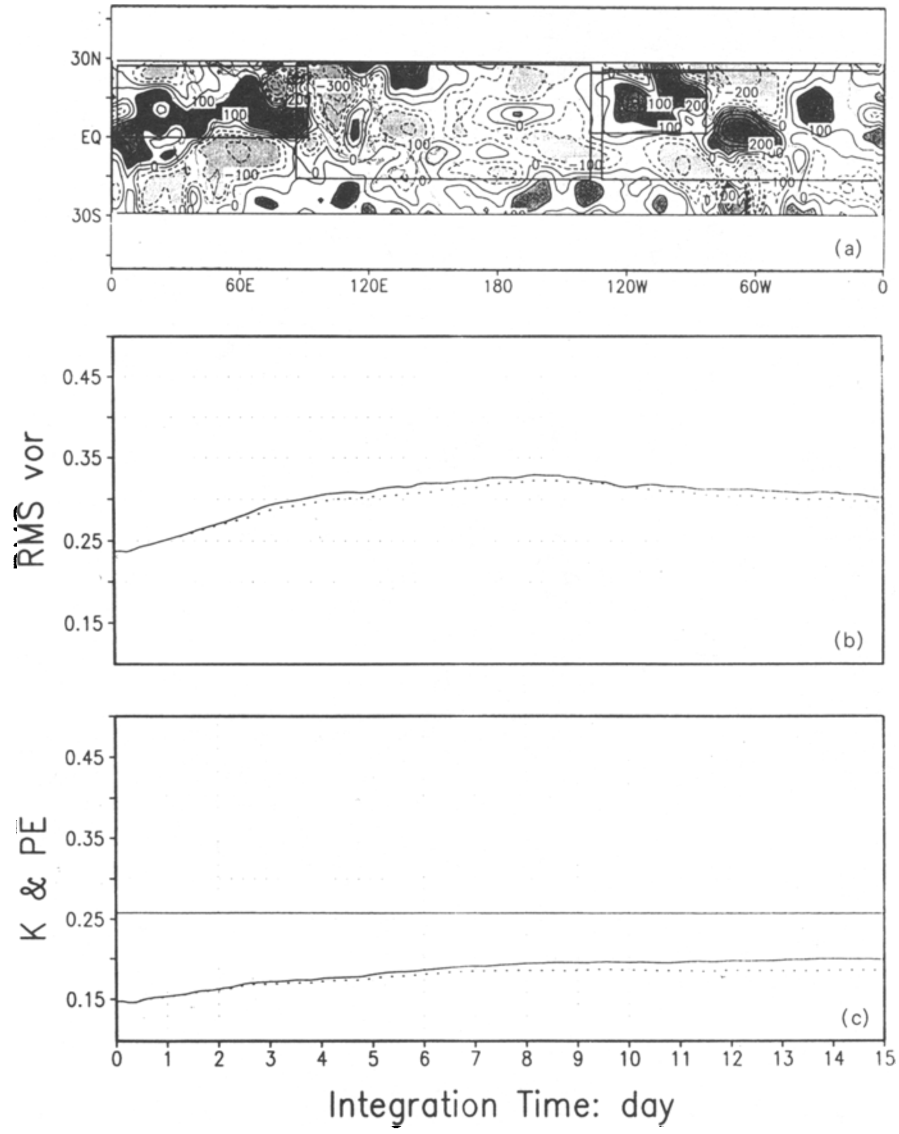

Fig. 8. Regions with changed heating for all experiments and the evolution of some statistical variables with time. (a) Regions with heating changed, and the background is the heating anomaly as Fig. 6c, (b) global RMS vorticity, unit: 10^{-4} s^{-1}, (c) Total kinentic and potential energy, unit: 10^5 kg m^2 s^{-2} and 10^8 kg m^2 s^{-2} individually. In (b) and (c), the solid line is for the experiment CLI_ht, the dashed is for the experiment 98HT.

of 4–5 days, and therefore the spin–up time of 4 or 5 days is enough.

The contribution to the maintenance of the blocking from tropical anomalous heating can be estimated by the comparison of the experiment 98Ht with CLI_ht, and the contribution from different tropical anomalous heating centers can be estimated by the comparison of CLI_ht with other experiments.

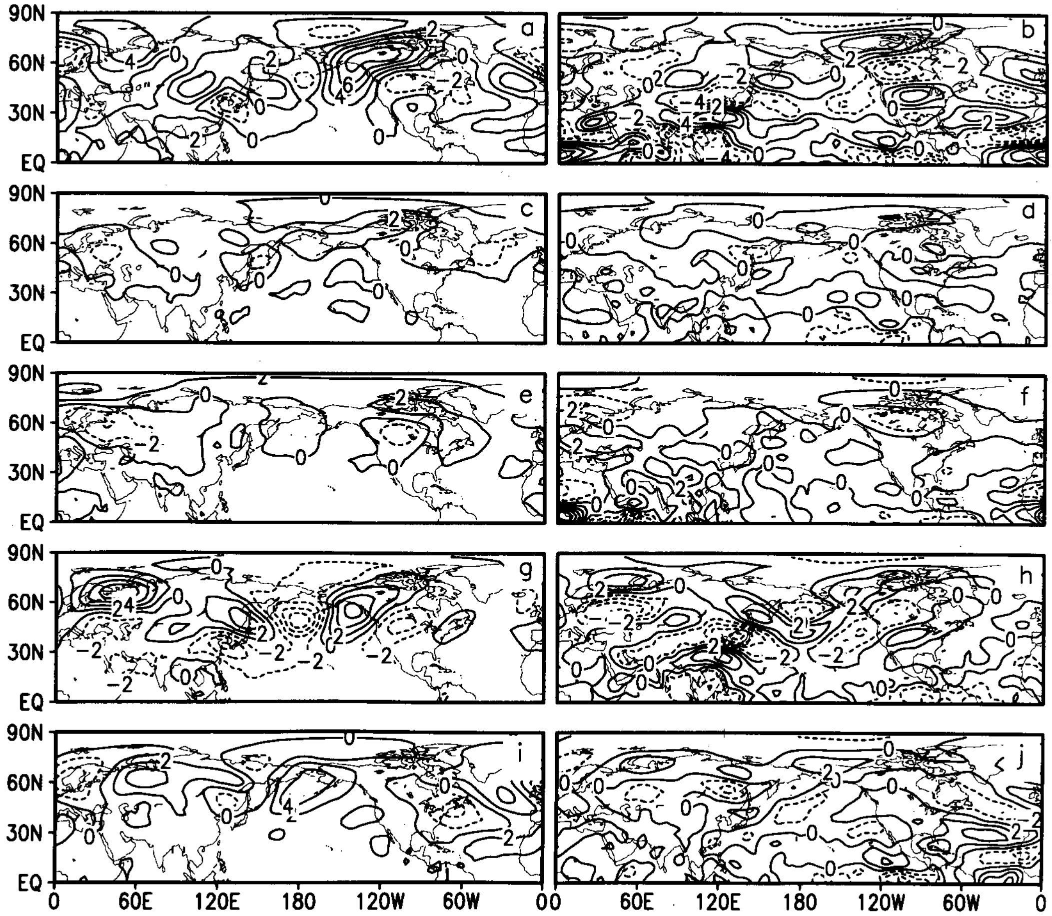

Fig. 9. 500 hPa height and 200 hPa zonal wind response difference between the experiments. Unit: dam in (a), (c), (e), (g) and (i), m / s in (b), (d), (f), (h) and (j). (a) and (b) are for 98HT_CLI_ht, (c) and (d) for 98HT_EP − CLI_ht, (e) and (f) for 98HT_INAF−CLI_ht, (g) and (h) for 98HT_CWP−CLI_ht, (i) and (j) for 98HT_AA − CLI_ht.

In Fig. 9a the response of height at 500 hPa to the tropical anomalous heating resembles the observed anomalies (Fig. 1b). There exists a positive anomaly center with the maximum value of more than 50 gpm near the Ural Mountains, a negative center around the Baikal Lake downstream of the Ural Mountains, and another positive center of more than 20 gpm over the eastern Siberia and the Okhotsk Sea, and these 3 centers together make up an anomaly pattern similar to the "twin blockings". Over other areas of the Northern Hemisphere, the anomalies are small, but the distribution pattern is similar to the observed one. In Fig. 9b, the response of the zonal wind at 200 hPa also resembles the observed one. There is a negative anomaly center of less than −2 m / s around the Ural Mountains, a positive anomaly on its southern and northern flanks, and a positive center of over 2 m / s over the sector from the northeastern Atlantic to Europe, which implies the acceleration of westerly over the central northern Atlantic and the deceleration over the Ural Mountains. All these simulated results demonstrate that the anomalous heating over the tropics contributes much to the maintenance of the Ural blocking in agreement with the diagnosis above.

The response of height at 500 hPa and zonal wind at 200 hPa to the abnormal heating over the tropical eastern Pacific (Fig. 9c–d) is much weaker than those in Figs. 9a–b, which shows that there is less contribution from the anomalous heating over the tropical East Pacific.

In Figs. 9e–f, the positive anomalous heating over the area including West Asia, the west of South Asia, the Arab Sea, and tropical Africa contributes to negative anomalies of height at the Ural Mountains, and thus does not favor the maintenance of the Ural blocking.

In Figs. 9g–h the response anomaly of 500 hPa height over Ural is over 8 dam, and there is the distribution pattern of " positive–negative–positive" over Eurasia, similar to the observed one. The response of 200 hPa zonal wind is less than −6 m / s around the Ural Mountains and positive on the southern and northern flanks of Ural, which shows that the westerly wind bifurcates and decelerates over the Ural Mountains, and also positive over the region from the North Atlantic to the west coast of Europe. These results show that the anomalous heating over the tropical central and western Pacific favors the maintenance of the Ural blocking. The response in Fig. 9g is similar to but greater than that in Fig. 9a, which suggests that the anomalous heating over the central and western Pacific favors the maintenance of the Ural blocking greatly.

Figures 9i–j give the response to the anomalous heating over the area from the tropical eastern Pacific to mid–America and the tropical Atlantic. The response of the height anomaly in Ural is greater than 4 dam, and positive over Eurasia and negative over the area from East Beigal Lake to Okhotsk Sea. The response of the zonal wind at 200 hPa is negative and less than −2 m / s at the Ural Mountains, positive on the southern and northern flanks of the Ural Mountains, which shows westerly bifurcation. The response is positive and greater than 2 m / s over North America to the Atlantic, which shows the eastward extension of upper jet. All results show that the anomalous heating from the tropical eastern Pacific to mid–America, the tropical Atlantic, favors the maintenance of Ural blocking. From Figs. 9c–d, we have pointed out that the anomalous heating over the tropical eastern Pacific has less contribution to the anomalous height, which indicates that the contribution in Figs. 9i–j is mainly from the tropical Atlantic. It is to say that the positive anomalous heating over the tropical Atlantic favors the maintenance of Ural blocking. In Fig. 1b the observed maximum anomaly over the Ural Mountains is greater than 14 dam, but in all experiments above the maximum response is not greater than 8 dam (see Fig. 9g), much weaker than the observed. It is not difficult to understand this point considering that all these experiments are on extended–range scale, in which forecasting depends on both the internal dynamics and external forcing, and the observed anomalies include the contributions from both internal dynamics and external forcing such as tropical heating. All experiments here are carried out with the same initial fields but different tropical heating, so only the contribution from individual different tropical forcings can be seen through the comparison among these experiments.

All the results above are on the basis of ensemble analysis, and their significance depends on the scatter among the members, and is yet to be justified. We address the significance check by comparing " intra–set" variance (i.e. between members of an ensemble) with " inter–set" variance (i.e. between 6 ensemble experiments) of the 500 hPa mean height. And the inter–set departure is significant only when they are much greater than the intra–set. We calculated the intra–set standard deviation of all the 6 sets (not shown), and found that they are below 20 gpm, much less than the inter–set (Figs. 9a, c, e, g, i), which suggests that the results are significant.

By the way, the wave–train–like anomaly distribution along the coast of eastern Asia is in agreement with Lu and Huang (1996), in which they studied the impact upon Northeast Asia blocking from the anomalous heating around the Philippine warm–pool.

All the results above suggest that the abnormal tropical heating, especially over the tropical central and western Pacific and the tropical Atlantic, favors the maintenance of the Ural blocking.

5. Summary and discussions

The enormous floods over the Yangtze River basin of China in the 1998 summer are mainly attributed to the recurrence of Meiyu and the abnormal extension of rainy season. The connection between abnormal Meiyu and circulation anomalies at the Ural Mountains is analyzed briefly, and it is found that the long persistence of the blocking at the Ural Mountains is one important aspect making up the circulation pattern of anomalous Meiyu. The maintenance of the Ural blocking is investigated from two aspects, internal forcing (synoptic–scale transient forcing) and external forcing (tropical anomalous heating) via diagnosis analysis such as adjoint sensitivity analysis, composite and E–vector analysis, and numerical simulations.

The results by diagnosis indicate that the maximum region of transient eddy activity (storm track) over the central Atlantic is evidently abnormal and stretches eastward to the coastal Europe during the period, so as to intensify the transient eddy activity upstream of the Ural Mountains. The analysis of adjoint optimal sensitivity perturbation (OSP) indicates that the eddies at suitable position can absorb energy from basic flow efficiently, and favor the triggering of internal model, hence the maintenance of the Ural blocking. The E–vector diagnosis and the results of linear stationary wave support this point further.

The diagnosis also indicates that the tropical heating, the mid–latitude upper jet and the Hadley circulation are evidently abnormal during the case period. As is well known that anomalous tropical heating can result in the anomaly of the Hadley circulation, and thus the upper jet. Although there is interaction between upper jet and transient eddy, the role of basic flow in modulating transient eddies is primary and important. So the enhancement of transient eddies activity upstream of the Ural Mountains can be attributed to tropical anomalous heating, at least partly. Tropical anomalous heating can also influence the stationary wave directly, hence the anomaly at middle and high latitudes. The conducted experiments clearly demonstrate the two–fold function of the tropical heatings.

To understand the possible mechanism responsible for the long persistence of the Ural blocking, we have analyzed the contributing factors in terms of internal dynamics and external forcings. Quite a few authors (e.g. Trenberth et al., 1999) have studied and summarized the possible mechanisms of persistent anomalies. Though it has been pointed out that the internal and external forcings often work in concert instead of being mutually exclusive, they are dealt as two independent mechanisms in most of the works.

The formation and maintenance of the blocking can be explained well when the internal and external forcings are taken into account together. The tropical anomalous heating can cause the anomaly of the stationary wave, with positive height anomaly at the Ural Mountains and the anomaly of upper jet. These two will modulate and re–organize storm track, in turn, lead to the enhancement of transient activity upstream of the Ural Mountains. The re–organized transient activity can further favor the increase of positive anomaly till the formation of blocking. This is a positive feedback of two–way interaction between transient eddy and stationary wave, and the tropical anomalous heating stimulates and helps to maintain this process. Though the response to the tropical heating itself may not reach the strength of blocking, it can be indispensable when it is involved in the internal dynamics. This is the point.

The analysis in the former section mentions that the tropical anomalous heating is related to the SSTA in the 1997 / 98 ENSO event. These results partly support the empirical finding that flooding is likely to occur in the following year of ENSO, normally the retreat phase. It suggests that the special distribution of SSTA should be taken into account, and that we cannot confine our sight to the impact of ENSO on the subtropical high over the western Pacific (SHWP), as most authors did so far. The impact on the mid–latitude circulation upstream, i.e. that from the tropical eastern Pacific and the Atlantic cannot be ignored (see also, Wang et al., 2000).

But there are some questions deserving to be discussed in this paper. In the context, we have used the concept of OSP (optimal sensitive perturbation) in an attempt to suggest a process of self–sustain, i.e. the slow varying basic flow decides the OSP, and the OSP acts to excite normal mode, thus maintains the basic flow. And the roles of tropical forcing are two folds: it excites Rossby wave to maintain the basic flow in one hand, and strengthens the mid–latitude upper jet, in turn, to reorganize the transients in the other. In this sense, the anomalous tropical heating, i.e. external forcing intervenes and promotes the operation of the two–way interaction mentioned above.

Some weakness of the approach used is also apparent. The OSP analysis used above is based on a linear framework assuming the slow–varying of the basic flow. This assumption may not be applicable in an episode of long duration. However, since we are dealing mainly with the problem of maintenance rather than a rapid development or decay, it is expected that the concept of OSP may serve as a clue to link the context of the background flow and feedback of perturbation. Nevertheless, we have to resort to numerical experiments for the further check.

As for the location and strength of observed transients, to a large extent, it is associated with the jet. The contribution of the tropical heating analyzed above only partly explains the strengthening of the jet. The feedback of eddies to the jet may also be essential. If the latter proves to make a major contribution, it could lower the predictability of the episode. This may involve another two–way interaction between the jet and eddies, which is beyond the scope of the paper.

We investigated the role of tropical abnormal heating in the maintenance of the blocking over the Ural Mountains. In fact, there is also significant anomaly of extratropical heating during the blocking period, what role these anomalies are playing has not been studied and remains to be explored. In addition, the data set of 1998 used here is not consistent with other years, which may lower the confidence of the results to some extent.

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1998 年夏第二阶段梅雨期乌拉尔山阻塞形势的维持

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摘　要

1998 年夏季长江流域发生了近 50 年来最严重的洪水。洪水形成最直接、最主要的原因是梅雨异常。异常梅雨的形成与东亚夏季风偏弱及热带外环流持续异常有关，其中一个明显特征是乌拉尔山地区长时间维持阻塞形势。本文结合诊断分析和数值试验，从瞬变对基本流的强迫(大气内部强迫)及热带热源强迫(外源强迫)两方面，分析了与第二段梅雨相对应的乌拉尔长时间阻塞的维持机制。利用共轭敏感性分析方法，计算了最有利于乌拉尔阻塞发展和维持的敏感扰动，发现扰动的分布位置，刚好与观测到的，从东大西洋到欧洲区域的异常增强的瞬变活动区相重叠。E 矢量及斜压线性静止波模式的诊断进一步表明，异常期间的增强瞬变活动有利于乌拉尔出现正高度异常。计算了持续异常期间的高空急流及大气加热场，发现北美到大西洋的高空急流及热带加热都出现明显异常。中期天气预报模式 IAP T42L9 的集合预报试验表明，热带地区的加热异常，尤其是热带中西太平洋和大西洋的加热异常，有利于乌拉尔正高度异常的形成。最后，提出了一种热带异常热源驱动下，瞬变波与定常波双向相互作用的阻塞形成与自维持的可能机制。

关键词: 乌拉尔阻塞，热带加热，瞬变，行星波，双向相互作用