On the Formation and Maintenance of the Persistent Anomalies of Summertime Circulation over the Ural Mountains①

Li Shuanglin (李双林), Ji Liren (纪立人) and Lin Wantao (林万涛)

LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029

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ABSTRACT

The formation and maintenance of the persistent anomalies (PA hereafter) of summertime circulation over the Ural Mountains are studied, and a two–way interaction of transient eddies and time–mean flow that may be involved in the evolution of the positive anomaly is demonstrated. Firstly the feature of synoptic–scale transient activity during the PA period is investigated based on composite, and the results suggest a significant enhancement of transient activity over the sector from the central North Atlantic to the coastal western Europe for the positive cases whereas a weakening is for the negative. Numerical simulations are conducted using a barotropic primitive equation model linearized about two time–mean flows, the composite of positive cases and the climatological July mean respectively. The results show that the enhanced transient activity upstream will favor positive height anomalies over the Ural Mountains. A barotropic stormtrack model is developed, by which the role of time–mean flow in organization and modulation of transient eddies is studied. It is shown that the growth of ridge over the Ural Mountains tends to organize transient eddies into the region upstream from the central North Atlantic to the coastal western Europe. Combining the two aspects, a positive feedback mechanism through two–direction interaction of transient eddies and basic flow is proposed, which can be responsible for the formation and maintenance of the persistent positive anomalies over the Ural Mountains.

Key words: Persistent anomaly, Transient forcing, Planetary wave, Two–way interaction

1. Introduction

The persistent anomalies of summertime circulation over the Ural Mountains are closely related to the drought / floods over East Asia, e. g., the abnormal Meiyu in 1998 over the Yangtze River valley and the associated flooding, the severest in the last 50 years or so, are mainly ascribed to the persistent circulation anomalies, among which one of conspicuous features is the long maintenance of the blocking over the Ural Mountains (persistent positive anomalies) (Tao et al., 1998; Huang et al., 1998; Wang, 2000; Wang et al., 2000; etc.). Therefore it is of practical meaning to study the formation and maintenance of persistent anomalies over the Ural.

There are some theories on the formation and maintenance of persistent anomalies at middle–and–high latitudes with intermediate time–scale, among which the forcing of

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synoptic–scale transient eddies upon time–mean basic flow is well documented (Green, 1977; Shutts, 1983; Dole, 1986; Holopainen and Fortelius, 1987; Vautard and Legras, 1988; Luo, 2000; etc.). However, it has not been established yet that the majority of the observed blocking events form due solely to the forcing by the high–frequency transient eddies. Some studies (e.g. Steward, 1993; Nakamura et al., 1997; Lu and Huang, 1998, 1999; etc) suggest that dynamical processes with time–scales longer than synoptic–scale eddies may also be operative in the blocking formation. Their individual importance of transients and low–frequency wave is not uniform over different regions. Liu and Wu (1996) studied the maintenance mechanism of four blocking anticyclones in different regions of the Northern Hemisphere, and pointed out that time–mean flow plays a more important role in the North Pacific blocking cases whereas transient eddies do in the Atlantic and Alaska blockings. Nakamura et al. (1997) compared the time evolution of prominent blocking flow configurations over the North Pacific and Europe based upon composites, and found that a quasi–stationary Rossby wave train is of primary importance in the blocking formation over Europe, whereas the forcing by transients is indispensable to that over the North Pacific. How about the Ural blocking? Ye et al. (1963) showed the important role of synoptic–scale migratory eddies in the formation and maintenance of the Ural blocking by their empirical and statistical work. Dole (1986) gave a hint that the transient forcing may play a more important role in the Ural persistent anomaly in comparison with that in the North Pacific and the Atlantic. Li et al. (2001) studied the contribution of the abnormal transient activity to the formation and maintenance of a prolonged blocking case of 1998, which is a critical system resulting in the abnormal Meiyu and severe floods, and also found that transient eddies play a critical important role. However, in general situation, this problem is not completely clear.

In this paper we will investigate the transient activity during the period of persistent anomaly over the Ural Mountains, and study the formation and maintenance of the positive anomalies with long duration and re–occurrence from the view of interaction of time–mean flow and transient forcing. In Section 2, a threshold to define a persistent anomaly case is introduced briefly, and the cases satisfying the definition over the Ural Mountains from 1980 to 1996 are identified. The transient activity expressed by synoptic–scale bandpass height variance at 500 hPa is investigated. In Section 3, the effect of abnormal transient activity upstream upon the positive anomalies is studied by numerical experiments of a barotropic linear primitive model under two different time–mean flows, i.e. climatological time–mean flow and composite mean flow of positive cases, respectively. In Section 4, the roles of basic flow with positive height anomalies over the Ural in organization and modulation of transient eddies will also be examined by a linear barotropic model referred to as a stormtrack model. The last section are the conclusions and discussions.

2. Transient activity during the period of persistent anomalies over the Ural Mountains

The daily reanalysis data set of NCEP/ NCAR from 1980 to 1996 is employed in this study. The threshold to define a case of Persistent Anomaly (PA hereafter) here is based on Dole and Gordon (1983, DG83 hereafter), but the height anomalies are normalized by zonal–mean standard deviation at the latitude of a key point. When the normalized anomaly is greater than 0.9 (less than –0.9) and remains for at least 10 days, then a positive (negative) case is defined. The anomalies have been low–pass filtered by 5–day running mean in order to get rid of the interruption to the defined case from synoptic–scale transient eddies. By this definition cases through the globe from 1980 to 1996 are identified. The results suggest (not shown) three major regions of occurrence at middle–latitudes (1) over the central North Pacific, (2) over the North Atlantic, and (3) over the Ural Mountains region, which are consistent with other studies (DG83; Li and Ji, 1994). The definition here is not only simple but also applicable for the whole globe, while that in DG83 is suitable only in the extra–tropics.

In the present study, the point (60°E, 60°N) is chosen to represent the key region of the Ural Mountains. The derived criterion of height anomaly at 500 hPa by this definition is equal to 82 m or so. The results show that there are a total of 13 / 9 cases of positive / negative anomaly over the Ural Mountains from 1980 to 1996, respectively.

The composite height and stream function anomalies at 500 hPa are calculated, and the two–side student–test for the significance of their individual difference to 0 is conducted. The results indicate (not shown) (1) the development of the persistent anomalies is primarily barotropic and (2) the circulation patterns are evidently different between the positive and negative anomalies over the tropical regions such as the western Pacific, the Indian Ocean, the eastern Pacific and the Atlantic, besides over the extratropics including the Ural Mountains itself. All these suggest: (1) the processes associated with barotropic dynamics play important roles in the formation and maintenance of the anomalies; and (2) anomalies do not occur solely over the Ural Mountains, but tend to occur simultaneously also over other regions including some tropical areas. This implies that the formation and maintenance of the Ural PAs might be related to the tropical abnormal heating.

Below we will investigate the transient activity during the anomaly period. It is represented by the mean bandpass variance of 500 hPa height with synoptic scale of 2.5–6 days, and calculated by a 31– point filter (Deng and Sun, 1994). The two maximum regions of transient activity (not shown) are located over the northern Pacific and over the eastern North America to the Atlantic, respectively, which are in agreement with climatology (Deng and Sun, 1994). Figure 1 presents composite anomalies of the bandpass variance of positive and negative cases, and their difference. For the positive cases (Fig. 1a), one can see three major regions of positive transient activity anomaly over the central North Atlantic to Europe upstream of the Ural, the Baikal Lake, and the central North Pacific, among which the first one is the maximum. The major negative anomalies are over the Ural Mountains, the eastern and western North Pacific, and the central eastern America to the western North Atlantic, among which the first is the greatest. The fact that the maximum anomaly region of transient activity is situated from the central northern Atlantic to the West Europe implies the eastward shift of the Atlantic storm track. For negative cases, it is approximately opposite from Fig. 1b. The point can be seen in Fig. 1c clearly. The similar anomalies of transient activity can also be found in the eddy kinetic energy at 200 hPa (not shown). All results show that the transient activity during the period of the Ural persistent anomaly is abnormal significantly.

3. Impact of transient upon the Ural positive anomalies

Now that the major anomaly of transient activity during the positive anomalies is located upstream of the Ural, it is natural to ask: how does it influence the positive height anomalies over the Ural? Will it be in favor of the onset of positive height anomalies? As is mentioned in Section 2, the barotropic dynamics plays an important role, therefore we can address the problem through numerical simulations by using a linear barotropic primitive equation spectral model. Below are the equations of this model

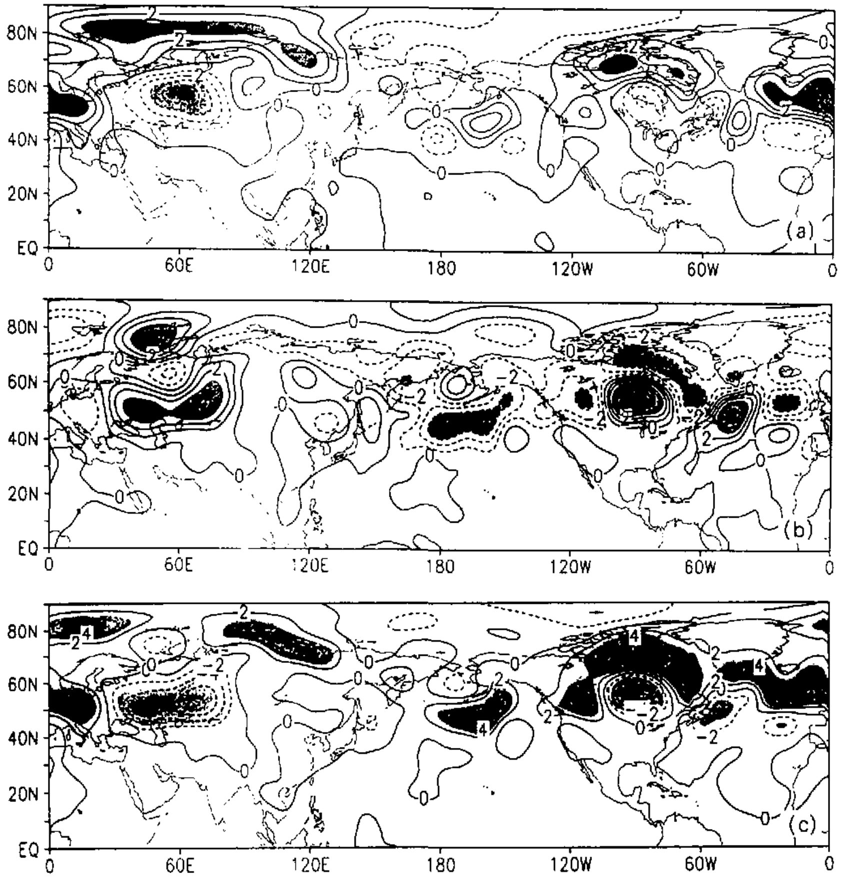

Fig. 1. Composite 500 hPa bandpass transient height variance anomalies to climatological same term, Units: 10^2dam^2. (a) For positive cases; (b) For negative cases; (c) the difference between (a) and (b).

$$\frac{\partial\zeta}{\partial t}=\frac{1}{a(1-\mu^2)}\frac{\partial}{\partial\lambda}(U\bar{\zeta}+\bar{U}\zeta)-\frac{1}{a}\frac{\partial}{\partial\mu}(V\bar{\zeta}+\bar{V}\zeta)-\kappa\zeta-\gamma\nabla^2\zeta, \qquad (1)$$

$$\frac{\partial D}{\partial t}=\frac{1}{a(1-\mu^2)}\frac{\partial}{\partial\lambda}(V\bar{\zeta}+\bar{V}\zeta)-\frac{1}{a}\frac{\partial}{\partial\mu}(U\bar{\zeta}+\bar{U}\zeta)-\nabla^2(\frac{U\bar{U}+V\bar{V}}{2(1-\mu^2)}+\varphi)-\kappa D-\gamma\nabla^2 D, \qquad (2)$$

$$\frac{\partial\varphi}{\partial t}=\frac{1}{a(1-\mu^2)}\frac{\partial}{\partial\lambda}(U\bar{\varphi}+\bar{U}\varphi)-\frac{1}{a}\frac{\partial}{\partial\mu}(V\bar{\varphi}+\bar{V}\varphi)-\tilde{\varphi}D-\kappa\varphi-\gamma\nabla^2\varphi. \qquad (3)$$

Here the bar denotes time mean, and the tilde global mean. $U=u\cos\varphi$, $V=v\cos\varphi$. $\bar{\varphi}$,φ are time−mean and deviation of geopotential height respectively, where height has its global mean removed. $\bar{\zeta}$ is absolute vorticity of the time−mean flow, γ, κ are the horizontal diffusion and the Rayleigh friction coefficient, respectively. All other notations are standard. Ting

(1996) demonstrated the equivalent–barotropic level in summer is situated below 400 hPa, thus it seems appropriate to use a barotropic model at 500 hPa for summer instead of 300 hPa for winter. It employs a spectral representation of all fields with a triangular truncation at wave number 21 (referred to as T21), and a time step of 45 minutes. The linear drag is particularly important in a linear model, so the value of Rayleigh friction coefficient κ is critical. We found that $\kappa = (15 \text{ days})^{-1}$ is appropriate, which ensures the total kinetic energy of perturbation to be approximately constant during time integration of the model. $\gamma = 5 \times 10^{16}$ m^4 s^{-1} can effectively damp the smaller scales at resolution T21.

Two sets of experiments have been conducted. In the first set, a positive vorticity perturbation is imposed in the region of observed maximum transient activity, and the model is integrated under two time mean basic flows, i.e., the composite of positive cases and the July climatological mean flow. The second set is similar to the first, but the imposed vorticity is altering with time. If the evolutions of the perturbation under the two sets of experiment are similar, it is expected that the enhancement of transient activity upstream will favor the development of positive height anomalies over the Ural.

Firstly we put an ideal initial perturbation with the maximum vorticity of 5.0×10^{-6} s^{-1} at the point of (0°E, 55°N) in an ellipse with a long axis of 60 degrees longitude and its short axis of 20 degrees latitude (Fig. 2a), which is correspondent approximately to a small perturbation over the observed anomalous transient activity region, i.e. the eastern coast of Atlantic, upstream of the Ural Mountains (see Fig. 1a). The integration results under the composite time–mean flow of positive anomalies show that positive height anomalies occur over the Ural on day 3 except that the maximum center shifts somewhat northward. Figure 2b presents the height response on day 7, from which one can see there are positive height anomalies over the Ural Mountains. This demonstrates that a positive vorticity perturbation upstream of the Ural Mountains under the time–mean flow of composite positive anomalies will result in positive height anomalies on day 7. The same experiment is conducted for the climatological July mean flow, and the result shows positive height anomaly response over the Ural Mountains too, similar to the composite basic flow (not shown).

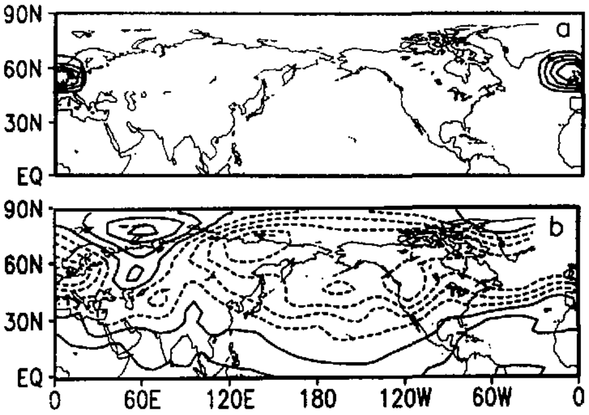

Fig. 2. Ideal initial vorticity distribution (a) and the height response on day 7 (b) with the time mean flow of composite positive anomaly cases. Units: s^{-1} in (a), and gpm in (b). Interval: 2.

But normally the perturbation vorticity upstream is not certainly positive, but more often is positive or negative alternately. In order to mimic this situation, an ideal perturbation source as Shutts (1983) was imposed at the region with the observed intensified transients, i.e. upstream of the Ural. The forcing evolves periodically and is expressed in the vorticity field as follows:

$$F = F_*(x,y)\cos(2\pi t/\tau).$$

Here $F_* = F_0\cos(\pi(\theta_x - \theta_1)/\Delta\theta)\cos(\pi(\varphi_y - \varphi_1)/\Delta\varphi$. τ, period, is equal to 5 days. $F_0 = 5.0\times 10^{-6}\mathrm{s}^{-1}$. Figure 3a displays the initial distribution of the ideal forcing source. Similarly we integrate the barotropic linear model under the two basic flows as above, i.e. the composite of positive anomalies and the July climatology mean. The results show that a positive height anomaly center occurs also over the Ural after day 3 for two basic flows, and remains in the whole integration. The maximum magnitude under the time–mean flow of positive composite is greater than that under the July basic flow. To give an example, Figure 3b presents the height response on day 8 under the time–mean flow of positive composite, from which one can see a significant positive height anomaly center over the Ural Mountains. These results show further that the enhancement of transient activity upstream is in favor of the maintenance of positive height anomalies over the Ural Mountains.

The result with the composite time–mean flow of positive cases is similar to those with climatological July, which may be related to that they have in–phase stationary wave. The calculation of 500 hPa height zonal deviation ($\overline{H}^* = \overline{H} - [\overline{H}]$) shows that the quasi–stationary wave during the positive composites is in phase with the climatological July (not shown), but has greater amplitude, which also indicates that the climatological background flow governed by topography and thermodynamic land–sea contrast is in favor of the positive height anomalies over the Ural, and thus leads to the preference of persistent anomaly at some

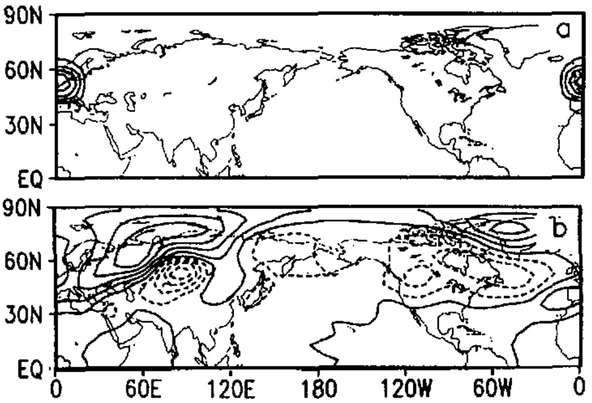

Fig. 3. Initial vorticity distribution (a) of ideal forcing field changing periodically with time, and the height response on day 8 (b) with the time mean flow of composite positive anomaly cases. Units: s^{-1} in (a), and gpm in (b). Interval: 2.

special regions as the Ural. In other words, here is provided a supplemental explanation to the geographic preference of persistent anomalies, at least for the Ural area. This also provides a clue to see how anomalous tropical heating might influence the nature and probability of the occurrence of persistent anomalies.

4. The organization and modulation of transient activity by time–mean flow

Below we will study the other aspect of the problem: whether and how does the planetary wave with positive height anomalies over the Ural Mountains favor the organization of transients upstream? We will address the problem by means of a linear barotropic model, which is able to describe transient activity and thus referred to as a storm–track model (here we refer to the major region of transient eddy activity as storm track).

A storm track model can be constructed by linearizing a GCM model. Branstator (1995) developed a storm track model under baroclinic schemes to study the role of low–frequent anomaly pattern in organization of transients. Because of zonal asymmetry of time–mean flow, the perturbations at various positions will not develop and evolve in the same manner when integrating the linearized model several days forward in time from random initial perturbations. The perturbations over some regions will develop rapidly while not over other regions. If many experiments as such are performed under the climatological mean flow, then the climatology of disturbances can be re–constructed. By tuning the amplitude of the initial perturbations, the amount of dissipation in the model and the length of each integration, the climatology can be regulated to approach the observed bandbass transients. In this way, the storm track can be simulated in a linearized model, in which non–linearity are not included. In a storm track model is the influence of time–mean flow upon transient organization concluded, but the feedback from transient on the time–mean flow is not. Therefore the role of time–mean flow in organization and steering transient eddies can be estimated by the comparison of storm tracks under different time–mean flows.

Now we construct a barotropic storm track model at 500 hPa on the basis of the barotropic primitive equation spectral model mentioned above, by which we study the transient activity under two kinds of time–mean flows: (1) the composite time–mean flow of positive anomalies over the Ural Mountains, and (2) a time–mean flow modified on the basis of (1). In (2), both the height anomalies and correspondent vorticity over the Ural Mountains decrease to 1 / 5 of its original value. Therefore, (2) is different from (1) only over the Ural Mountains. Fig. 4 displays the 500 hPa height of the two time–mean flows.

Figs. 5a, 5b present the simulated variance of transient height under the two time–mean flow. It can be seen that the two major regions of transients are over the North Pacific and the North Atlantic, respectively, which is approximately consistent with those observed. Figure 5c illustrates the difference of transient height variance under the two time–mean flows. One can see clearly that there are positive anomalies over the coastal West Europe upstream of the Ural, which implies that the transient activity upstream will intensify when the height positive anomalies over the Ural develop.

The above–mentioned results indicate that the positive height anomalies at the Ural Mountains will be in favor of the enhancement of the transient activity upstream. The stronger the ridge, the more active the transient eddies upstream. In other words, the occurrence of positive height anomalies, i.e. the growing of ridge over the Ural along with the upstream jet, will organize transient eddies into such a position that it most favor the further development of the anomalies.

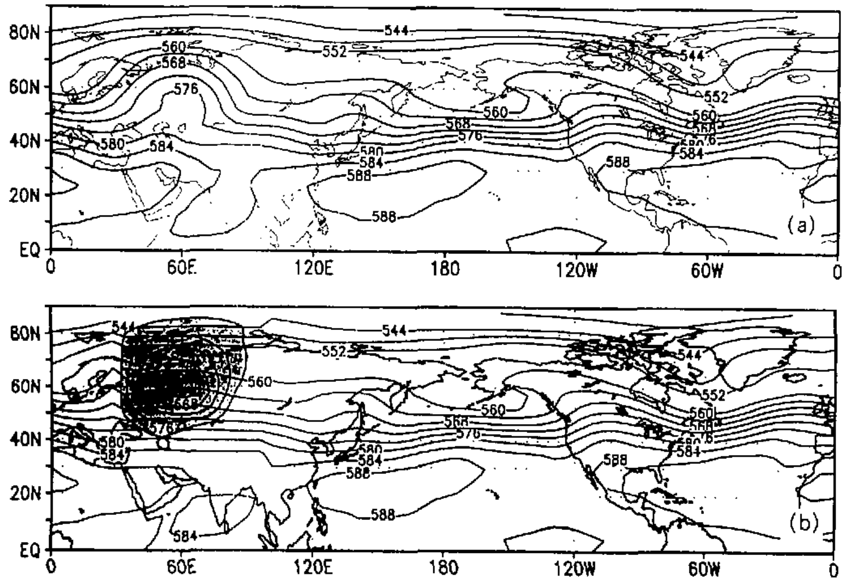

Fig. 4. 500 hPa height (in dam) of two time-mean flows for storm track model. (a) For the composite of positive cases; (b) modified based on (a), shaded is the modified region of height anomaly.

5. Conclusions and discussions

The formation and maintenance of the persistent anomaly of summertime circulation over the Ural Mountains are studied in the viewpoint of interaction between transient eddies and planetary–scale basic flow in this paper. We have already demonstrated that: (1) transient eddies tend to be organized upstream from the central Atlantic to the western Europe upstream when positive height anomalies occur over the Ural, (2) the enhancement of transient activity upstream of the Ural will be in favor of the development of positive height anomalies, and (3) the greater the height anomalies over the Ural, the more favorable for the transient eddies to be organized upstream. Summing up all these results, a mechanism for the formation and maintenance of the persistent positive anomalies over the Ural Mountains can be proposed. It can be described as below: firstly, positive height anomalies are initiated over the Ural for some reasons, for example, by the consistent forcings of abnormal tropical heating etc. (Li et al., 2001; Shukla and Wallace, 1983). Though the strength of the anomalies at the initial stage might not be great enough to define a blocking event (persistent anomaly event), the resultant planetary wave anomalies will be in favor of the shift of the Atlantic storm track eastward, thus the enhancement of transient activity at the coastal Europe, upstream of the Ural. The enhanced transient activity upstream will, in turn, boost the further enhancement of the positive height anomalies. Consequently, through the positive feedback by consistent two–way interaction between transients and slow–varying flow, the positive persistent anomalies would form and last for a long time. This mechanism can be summed up into a schematic view in Fig. 6.

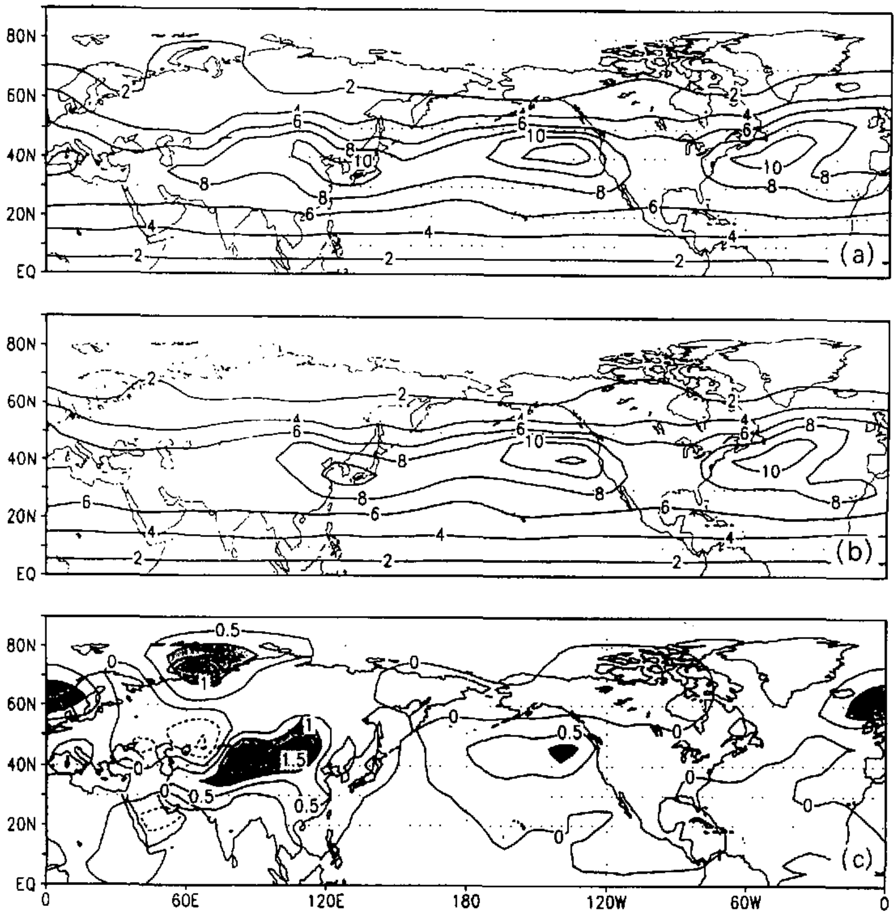

Fig. 5. (a) The variance of transient height by storm track model under time–mean flow of composite positive cases. Units: dam^2. (b) As in (a), but for the modified basic flow (see Fig. 4b). (c) The difference between (a) and (b).

Here we studied the role of two–way interaction between planetary wave and transients under linear and barotropic schemework. Strictly speaking, complete consideration should include nonlinear baroclinic dynamics. But as for the onset of persistent anomaly, linearization is a good approximation. Nonlinear baroclinic life cycle studies, like that of Simmons and Hoskins (1978), have found that though momentum fluxes by the eddies are present during the initial linear growth of a disturbance, it is not until the nonlinear decay stage that these fluxes become significant. Therefore nonlinearity is only needed to produce complete life cycles (Branstator, 1995; Cai and Mak, 1990). For the onset and maintenance of the persistent anomalies over the Ural Mountains, as mentioned in the previous section, barotropic process plays a more important role. This point is also demonstrated by Branstator (1995).

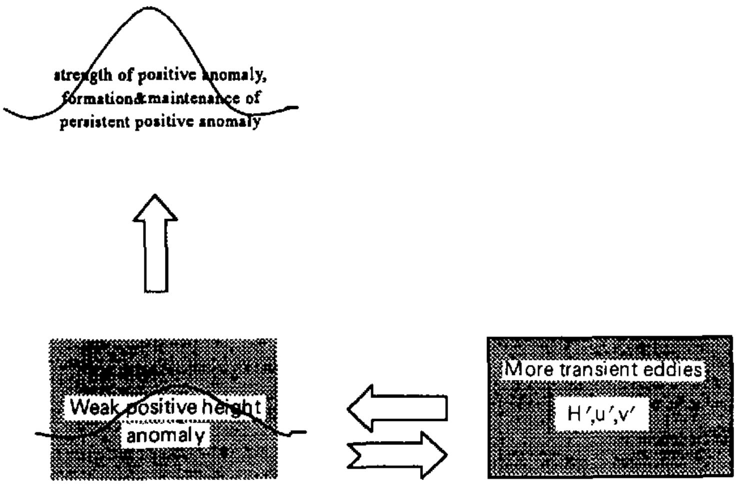

Fig. 6. Schematic view of the formation and maintenance of persistent positive anomalies through two-way interaction between transient eddies and planetary wave under the background of tropical abnormal heating.

An unsolved and key aspect of the mechanism above is the production of the initial positive height anomalies over the Ural. In general, mechanisms that could produce low-frequency anomaly, such as energy dispersion and barotropic instablity of basic flow etc., may serve. Li et al. (2001) in their 1998 case study showed the tropical abnormal heating can act as a source of Rossby wave resulting in the response at the Ural. Now, one may naturally ask whether all large-scale anomalies can induce a positive feedback from transient eddies, thus lead to persistent positive anomalies such as blocking. This question was not addressed here. But from other studies (e.g. Branstator, 1995; Whitaker et al., 1994) the answer seems to be negative. So, the mechanism proposed here could be applied to some anomaly pattern but not others.

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夏季乌拉尔地区大气环流持续异常的形成与维持

李双林　　纪立人　　林万涛

摘　要

从天气尺度瞬变涡旋与时间平均基本气流双向相互作用建立异常型的角度，研究了夏季乌拉尔地区大气环流持续异常的形成与维持. 首先基于合成分析，研究了持续异常期间的天气尺度瞬变波活动情况，结果表明: 正异常时，在上游地区，从北大西洋中部到西欧沿岸，瞬变活动明显增强. 负异常过程时相反，该地区瞬变活动减弱。利用线性正压原始方程模式，研究了在合成正异常基本流及 7 月气候基本流等两种基本流下，正异常时上游异常瞬变活动对异常建立的贡献。结果表明: 正异常时，上游增强的瞬变波活动有利于正异常的建立与维持. 利用基于线性正压原始方程模式设计的风暴轴模式，研究了时间平均基本流在组织与调控瞬变活动中所起的作用。结果表明: 当乌拉尔地区高压脊发展时，有利于瞬变在上游的北大西洋中部到西欧沿岸地区组织起来. 脊发展越强，越有利. 结合上述两方面的结果，提出了瞬变与行星波双向相互作用的乌拉尔持续正异常形成和自维持机制.

关键词: 持续异常, 风暴轴, 行星波, 双向相互作用