WAVE-FLOW INTERACTIONS IN THE ATMOSPHERIC LOW-FREQUENCY VARIATION OF BLOCKING PATTERN*

GAO Shouting (高守亭),

State Key Laboratory of Atmospheric Boundary Layer and Atmospheric Chemistry, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029

ZHU Wenmei (朱文妹)

Chinese Academy of Meteorological Sciences, Beijing 100081

and *DONG Min* (董 敏)

National Climate Center, Beijing 100081

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ABSTRACT

Through a simple review of low-frequency variation of blocking pattern and diagnoses of observational data and combining some experience in forecast practice, we put forward some thought about the mechanism of formation and maintenance of the blocking flow pattern from the synoptic/climatological point of view. It is emphasized that eastward moving and deepening of troughs in the upstream of the blocking high, the SST anomalies and topography effect are the main factors of impelling the variation of the blocking high. During the maintenance of Ural blocking high wave-flow interactions are studied through disposition of baroclinic trough (transient wave) and the blocking flow. This study will offer a primary basis for the further theoretical study on the formation mechanism of the blocking high.

Key words: low-frequency variation, blocking high, wave-flow interaction

I. A SIMPLE REVIEW OF LOW-FREQUENCY VARIATION OF BLOCKING PATTERN

To study the low-frequency variation, the first step is to define what is the low-frequency variation. The so-called low-frequency variation occurring in the Northern Hemispheric atmosphere is referred to any events with the periods longer than two weeks (including 30—60 day low-frequency oscillation).

Figure 1 is the climatic geopotential height distribution on 500 hPa for January plotted from NCEP (National Center for Environmental Prediction) reanalysis data of 1982—1994. It shows a typical three-wave pattern. If it is regarded as the multi-year climatological normal (of course, time series of data is not long enough), we can say in

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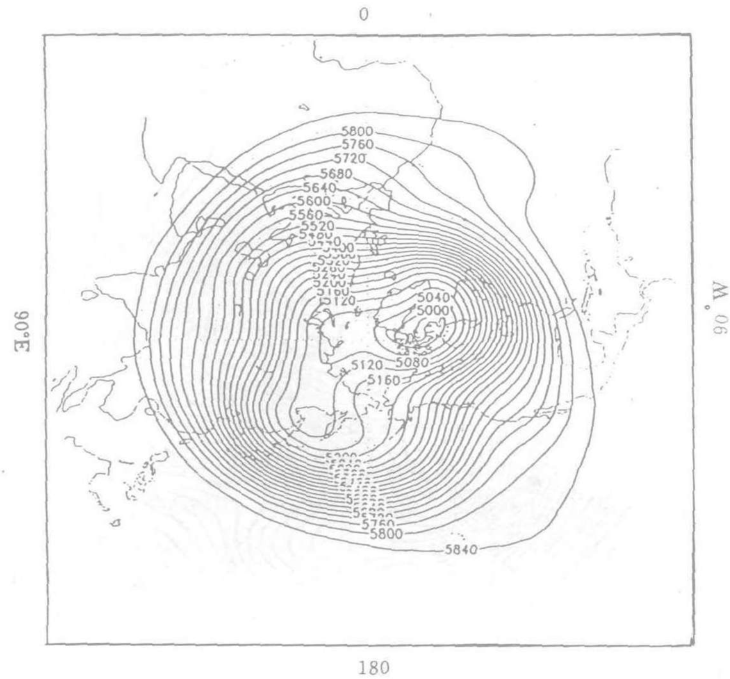

Fig. 1. The mean geopotential height distribution on 500 hPa for January (isopotential interval: 40 gpm).

January low-frequency events of the Northern Hemisphere is three-wave pattern around North Pole. If there exists a flow pattern deviated from the three-wave pattern, then low-frequency variation of blocking pattern occurs. Figure 2 shows a composite blocking pattern in the East Pacific (Tschuck 1994). It can be seen that the very strong blocking high locates in the East Pacific and west coast of North America. Compared with Fig. 1, the flow pattern of the blocking high departs far from its average position. Therefore, this kind of phenomenon indeed belongs to low-frequency variation of blocking pattern.

What are factors causing such persistent anomaly? This is the second question to be answered. The method of answering this question in traditional way is to analyze zonal flow stability through small perturbation. It is usually referred to Charney or Eady's baroclinic instability (1947; 1949). Thirty years later, Charney was enlightened from the modified theory of nonlinear resonance developed by Egger (1978), then he changed his idea and claimed that it is unreasonable to regard the persistent ridge in Fig. 2 as a perturbation from the zonal mean flow. Instead, he investigated a simple dynamic model—equivalent-barotropical potential vorticity conservation model in rectangle geometry. By using a very simple low-order truncation method, Charney and Devore (1979) got the multi-equilibrium solution (Fig. 3).

Figure 3 shows that there are one or three solutions (u_0) according to wavelengths (L). When $L \leqslant 2 \times 10^6$ m, only one solution exists. With L increasing, three equilibrium solutions appear. The high u_0 links with the zonal circulation pattern, while the low u_0, with meridional circulation pattern.

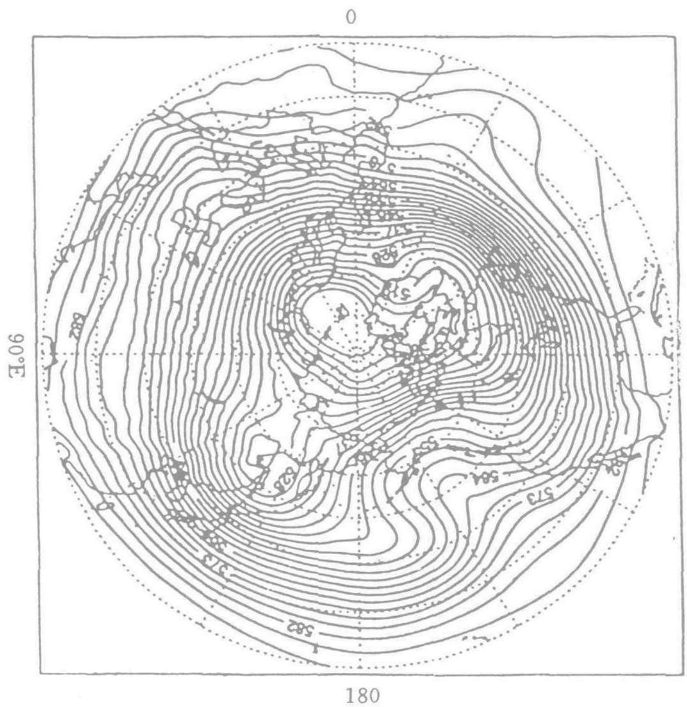

Fig. 2. Composite blocking flow pattern in the Pacific (Tschuck 1994).

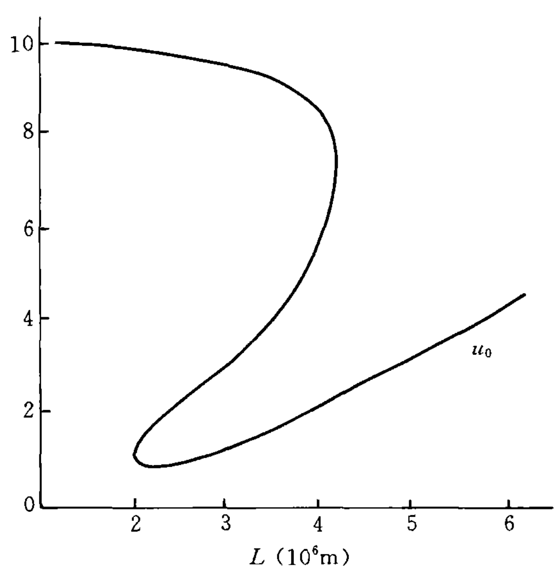

Fig. 3. Equilibrium solutions as a function of wavelength (L) and stable balance velocity component (unit: m s^{-1}) (Charney and Devore 1979).

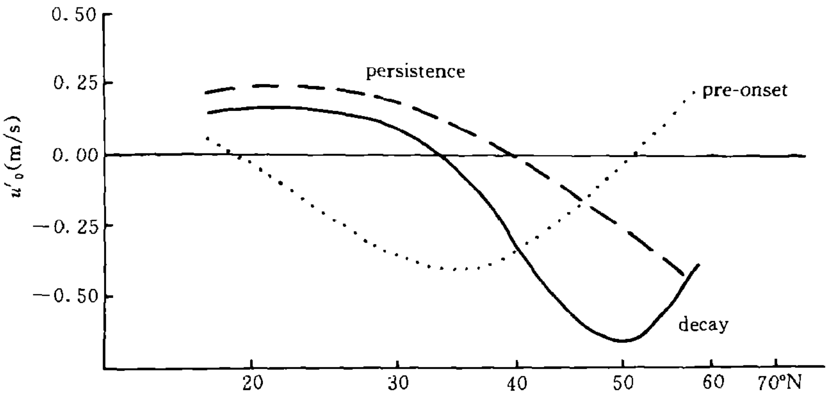

Fig. 4. The departure of zonal mean wind from its climatological normal during the three stages of blocking (Metz 1985).

CDV (Charney and Devore 1979) model is not realistic. It exaggerates the effect of topographic torque from the view of dynamics, and it excludes the stability of motion and physical processes and energy conversion.

Metz (1985) drew the conclusion as Fig. 4 from a series of detailed data analysis. It is shown that the departure of the zonal mean wind from climatological normal during the three stages of blocking (pre-onset, persistence and decay) is so small that the equilibrium solution of CDV model does not exist in the real situation. Hence CDV model can't be used as the basic model of dynamics of large-scale circulation pattern. CDV model can be only used as the purpose of explanation not to conduce to setting up a large-scale circulation pattern and relationship among multi-equilibria.

To study the translation between the zonal and blocking equilibria, it is necessary to add some perturbations to the equilibrium solution. It can be done by increasing dimensions of model or to choose another simple way that to add stochastic noise to CDV model. Egger (1981) used the second method at first, and then Benz et al. (1984) proposed the stationary wave resonance theory to explain the formation of blocking. However, all the above explanations are not successful.

Shutts (1983) reviewed all kinds of theories on the formation and maintenance of blocking in his Ph. D dissertation "Eddy Vorticity Forcing of 'Blocking' Flow Fields". He showed more appreciation to Austin (1980)'s proposition, that is, transient eddies play an important role in the maintenance of blocking overcoming surface friction. The key point of his dissertation is when transient eddies enter the blocking zone, eddies will be compressed in the east-west direction and extended in the south-north direction. Thus the local enstrophy cascade intrudes the blocking flow so as to overcome friction (Fig. 5).

Chinese meteorologist Li (1991; 1993) wrote a book named "Low-Frequency Oscillation in the Atmosphere", in which he proposed that 30—60 day oscillation exists evidently in the form of EAP (Eurasian Pattern) and PNA (Pacific-North American Pattern) teleconnection and wave train propagation in mid-latitudes. In his book entitled "An Introduction to Dynamical Climate", Li reviewed several formation mechanisms of blocking, such as multi-equilibria, nonlinear resonance, soliton and dipole theory. Lu and

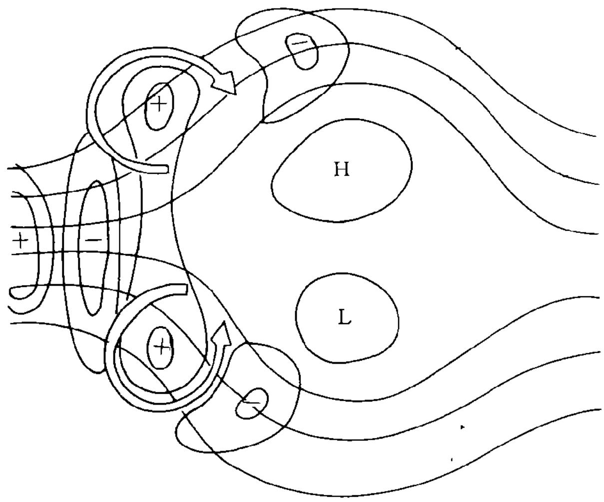

Fig. 5. The interaction between transient wave and blocking flow (Shutts 1983).

Huang (1996) investigated more about the blocking in the view of wave-flow interaction. and got many significant results.

In this paper the different points from above studies lie in emphasizing the observational facts and their diagnoses. match-ship of waves and blocking from viewpoint of synoptic meteorology and roles of waves in the maintenance and collapse of blocking. and providing some direct clues to the blocking prediction.

II. SOME PRELIMINARY VIEW OF THE BLOCKING FORMATION IN THE LOW FREQUENCY ANOMALIES

The blocking is one of the main phenomena in the low frequency anomalies. In the Atlantic. persistent abnormal blockings occurred in late January — March of 1946. late December—March of 1962. and in the period of December 1976—February 1977. Figure 6 shows the averaged 500 hPa January wind field plotted from 1982—1994 NCEP data. It is clear that there is an apparent wave-like feature in mean flow in the Northern Hemisphere compared with smooth mean flow in the Southern Hemisphere. This indicates that the mean flow itself presents some wave-like feature due to the effect of land-sea contrast. Hence. such large-scale low-frequency anomaly should be attributed to the anomalies of the basic flow. From this point of view. the blocking high can be named as blocking flow.

One of the questions is what causes so much change of the mean flow that strong and persistent blocking highs appear? Another is why such blocking highs appear frequently in some particular regions. such as the East Pacific—the west of the North America. Ural Mountains in the Eurasian Continent and the Atlantic Ocean? If we consider it only from the viewpoint of wave-flow interactions. it is difficult to explain the formation of such strong and persistent blocking. We admit that transportation of wave momentum flux and wave heat flux plays an important role in mean flow variation. but their roles appear mainly in the maintenance of the blocking (details in the next section). In fact. so far the

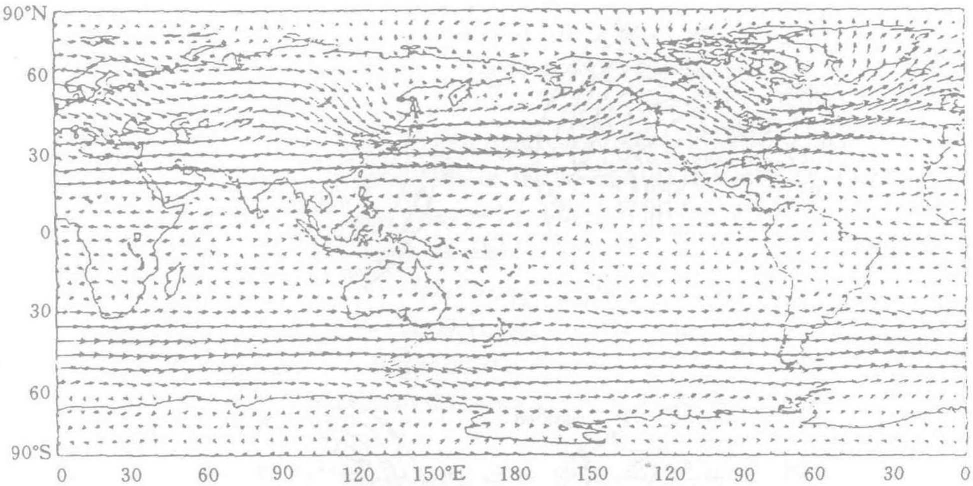

Fig. 6. The January averaged wind field on 500 hPa.

anomaly of mean flow is an unsolved problem and it is one of difficult points of research subjects. If the multi-equilibrium framework is accepted, it is difficult to explain why there are multi-equilibria in the atmosphere. Until now, the barotropic or revised equivalent barotropic vorticity equations, even baroclinic model, can only obtain one to three real solutions. However, the real atmosphere may show more than three equilibrium states. Figure 7 is the examples of 4 equilibrium states in the northern atmosphere (Dole 1982). There is no idea to use three equilibrium states to explain the four or more state regimes.

When Dole did this job, multi-equilibrium states and blocking problems have been the controversy focus among meteorologists. Therefore, he tries to avoid using these words and only referred them to positive or negative anomalies. He defined the 30-year averaged flow pattern as the climatological normal, and an anomaly as the departure from the climatological normal. From the figures provided by Dole, it can be seen that the multi-equilibrium states in the atmosphere do exist, and of which we are hard understanding.

30—60 day low-frequency oscillation (LFO) was found first in the tropics (Madden and Julian 1971). Later, people also found that LFOs exist in the mid-latitudes (Li 1991), and they are particularly strong in the Northern Hemisphere in winter. Therefore, people infer that such oscillations or strong anomalies are caused by interactions between the westerly and the topography in the middle and high latitudes. However, the blocking high in the Pacific seems to be no relationship with the topography, these puzzles are still difficult to understand.

Our preliminary standpoint is that, because blocking is the anomaly to the basic flow, its suitable name should be blocking flow, just like the viewpoint of Shutts (1983) et al., therefore, it should belong a part of flow rather than wave. Much evidence supports this standpoint. The thesis of Lejenas and Madden (1992) entitled "Travelling Planetary-Scale Waves and Blocking" is the most convincing one. They meticulously

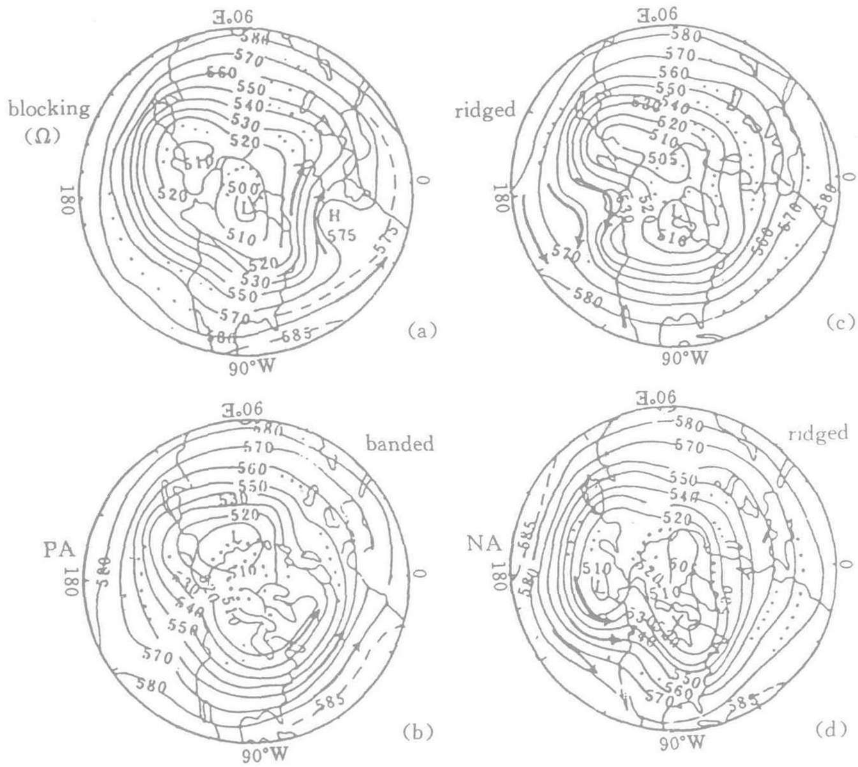

Fig. 7. The persistent anomaly regimes on 500 hPa. (a) and (b) are the positive and negative anomalies in the Atlantic: while (c) and (d) are for the Pacific (Dole 1982). The contour interval is 10 gpm. PA indicates positive anomaly and NA negative anomaly.

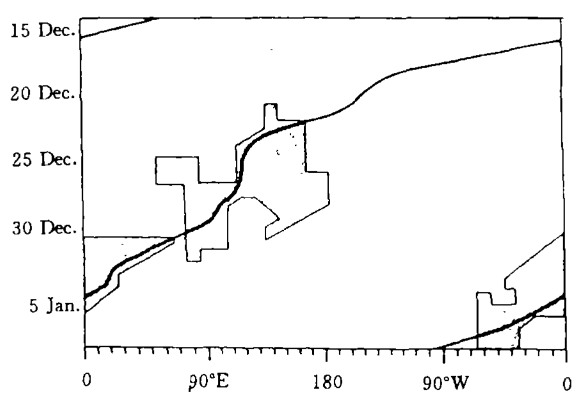

Fig. 8. The example of westward propagation wave-1 meeting with the blocking flow at 60°N (Lejenas and Madden 1992) (The period is 15 Dec. 1954 to 8 Jan. 1955. The circumferential line represents the blocking range at 60°N in different time).

analyzed the relation of westward wave-1 and wave-2 with the blocking. and indicated wave-1 contributes more to the blocking flow than the wave-2. They also showed the example of westward propagation wave-1 meeting with the blocking flow (Fig. 8). Meanwhile. we think that there are three main factors contributing to the formation of the blocking flow.

The first fact is that the trough in the upstream of blocking flow moves eastward and deepens. This phenomenon appears clearly in the formation of blocking in the two oceans. From Fig. 1. it can be seen that the averaged position of East Asian trough locates to the west of 160°E. But from Fig. 2 we can see that the East Asian trough expands eastward to 180°E and deepens. as a result. the warm advection ahead of the trough became stronger and pushed northward to impel the formation of the warm blocking in the East Pacific. In the similar way. the deepening of the North American trough accelerates the blocking formation in the Atlantic. which can be seen from the comparison between Fig. 1 and Fig. 9.

The above facts tell us that deepening and eastward expanding of the East Asian trough and the deepening of the North American trough play an important role in the formation of blocking in the two oceans.

The second is the air-sea interactions. Jiang and Wallace (1991) calculated the simultaneous correlation between the 11-year monthly averaged 500 hPa height from November to April of next year and the SST near the Newfoundland (TAN) in the Atlantic and the SST near the Bermuda (TAS) (data ranging from 1950 to 1979). The

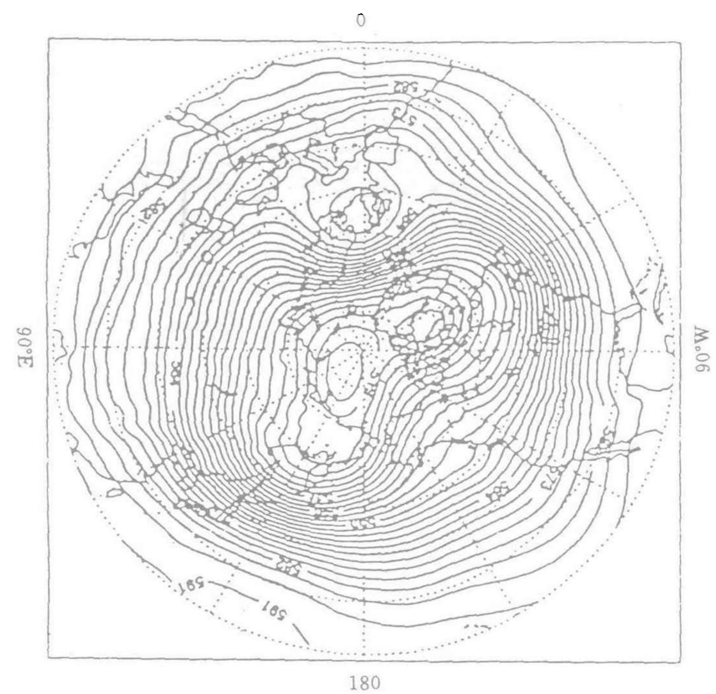

Fig. 9. Composite blocking flow pattern over the Atlantic (Tschuck 1994).

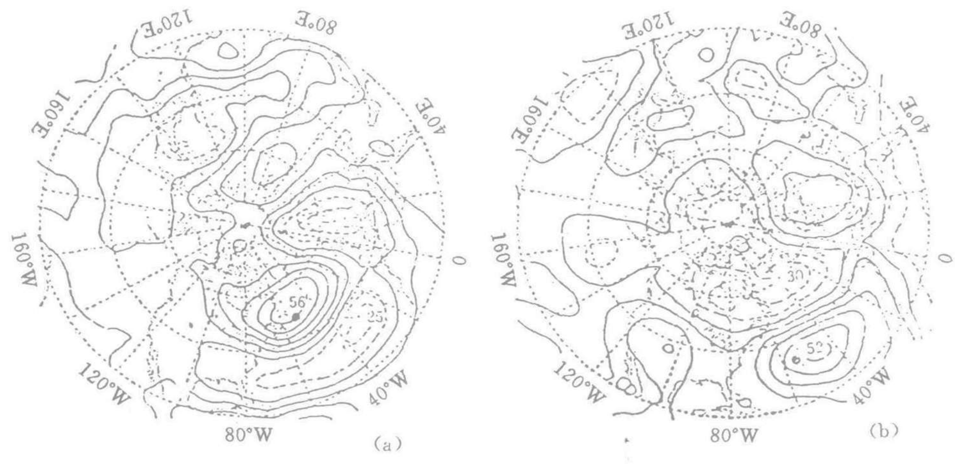

Fig. 10. Simultaneous correlation distribution of 500 hPa height and sea surface temperature in winter half year (November to April) of 1950—1979 (Jiang and Wallace 1991). (a) TAN; (b) TAS.

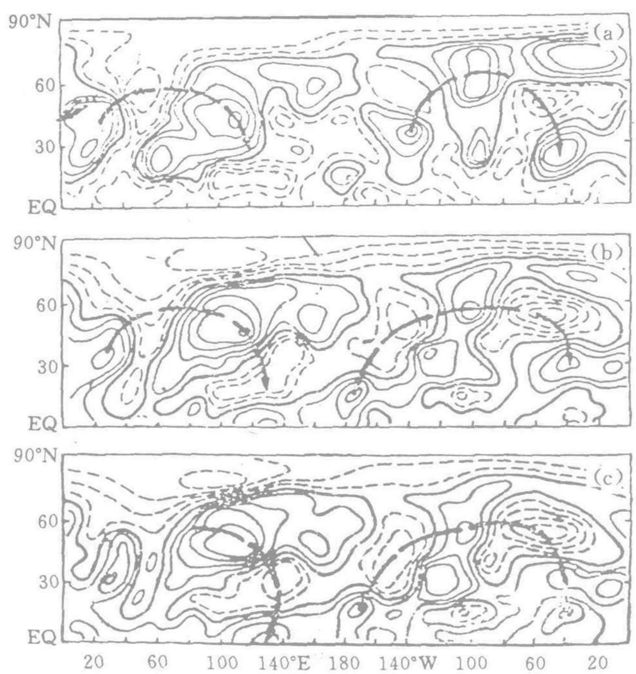

Fig. 11. 30—60 day low frequency teleconnection patterns on 500 hPa height. The solid line and dashed line denote the positive and negative correlations, the contour interval is 0. 2. The reference point is 45°N, 115°E (Li 1993).

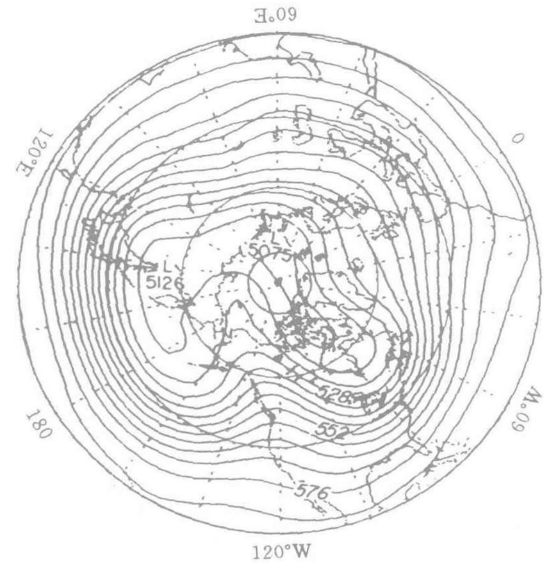

Fig. 12. The composite PNA pattern (Wallace and Gultzler 1981).

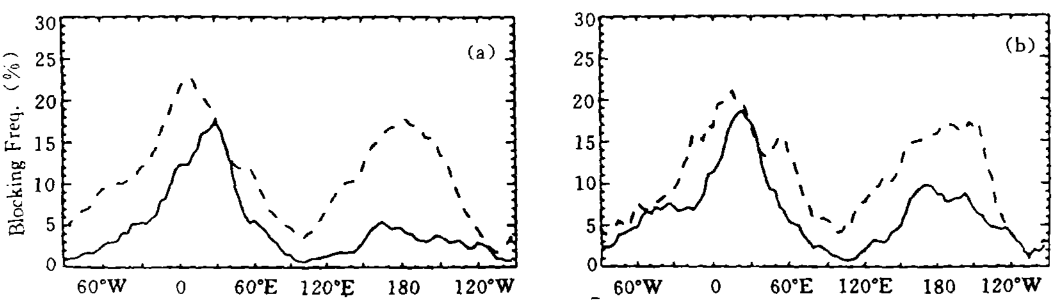

Fig. 13. (a) The blocking response over ocean (dashed line) to the fixed SST (real line) in the equatorial East Pacific (Bengtsson 1996). (b) The blocking response over ocean (dashed line) to the observed SST (real line) in the equatorial East Pacific.

result is shown in Fig. 10.

From the correlation maps it can be seen there is evident positive correlation between the Atlantic SST and the 500 hPa height. Thus the positive temperature anomalies in the mid-latitudes and high latitudes in the Atlantic facilitate the formation of the blocking in those regions. In fact, the time scales of the response of atmosphere to oceanic heating range from several days to weeks. From the viewpoint of climatology, the atmospheric response to the sea temperature variation is considered as simultaneity.

The low-frequency anomalies in the Pacific are related to the SSTA in the equatorial Pacific. According to Li (1993), the atmospheric tele-response to the SSTA in the equatorial Pacific is mainly 30—60 day low-frequency tele-response, and in the mid and high latitudes 30—60 day oscillations in the atmosphere are excited, which show two

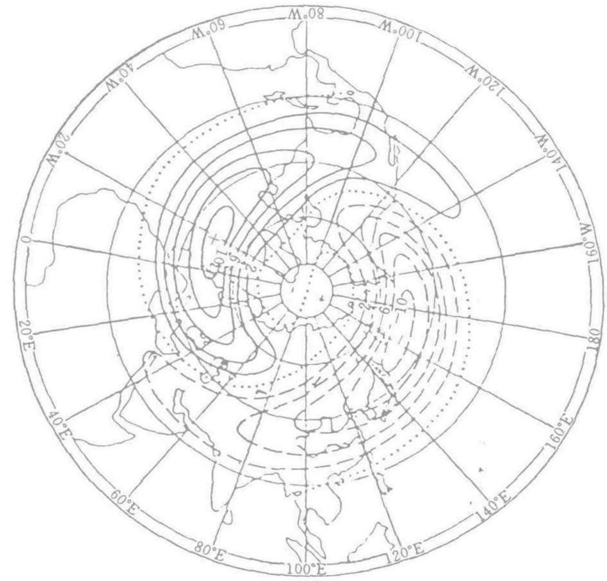

Fig. 14. Wave-1 distribution in January (dagpm).

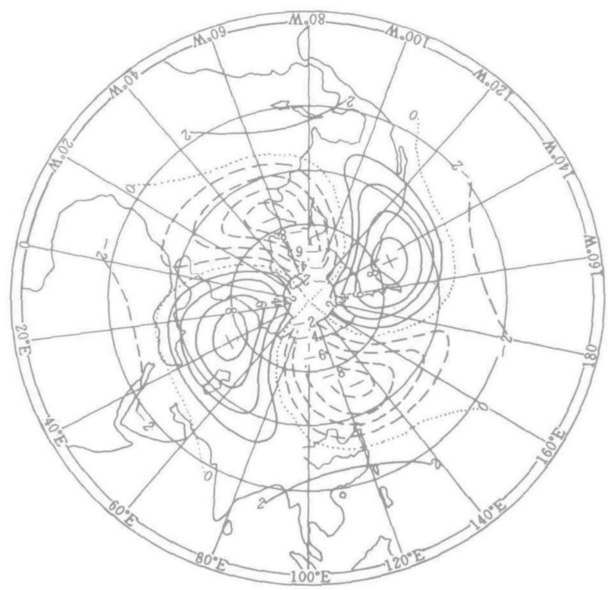

Fig. 15. Wave-2 distribution in January (dagpm).

stable basic teleconnections. One is EAP pattern (EurAsia-Pacific pattern), the other is PNA pattern (Pacific-North American pattern) (Fig. 11).

Figure 11 shows the remote linkage of PNA Pattern with the SSTA in the equatorial Pacific. This is the typical low-frequency anomalies in Fig. 2 when typical PNA patterns are composited. About this, through comparison of Fig. 12 with Fig. 1, we can see that both flow patterns are the same.

The blocking in the East Pacific can be seen as the typical PNA Pattern. Many of researches indicate such a fact that the atmospheric response to the heating in the equatorial Pacific can reproduce the PNA teleconnection (Webster 1981). Meanwhile, the period from December to February is the best coupling time of air-sea interaction. Thus, the blocking anomalies in the East Pacific are closely related with the air-sea interaction, which will be proved in Fig. 13.

The third is the contribution of westward propagation wave-1 and wave-2 to the blocking flow. In high latitudes, the amplitude of Rossby wave is relatively small due to relatively small beta effect and relatively weak baroclinity. Therefore, the blocking flow presents equivalent barotropical structure. Thus it is difficult for us to accept the viewpoint of the so-called baroclinic resonance curvature of blocking formation. But we indeed think that the wave-flow interaction is particularly important for the maintenance of the blocking flow. The westward propagation of wave-1 facilities the formation of blocking flow in the Pacific while the westward propagation of wave-2 facilities the formation of blocking flow in the Atlantic, the other short waves are relatively unimportant.

From Fig. 14 and Fig. 15, it can be seen that westward propagation of wave-1 right imposes positive allohypse on the blocking flow over the East Pacific, and wave-2 brings the positive allohypse to Atlantic blocking.

Lejenas (1992) et al. discussed the roles of wave-1 and wave-2 in the blocking flow, especially, how the westward propagation of wave-1 impacts the wind field of the blocking flow.

III. THE EFFECT OF WAVE-FLOW INTERACTION ON THE FORMATION AND MAINTENANCE OF URAL BLOCKING

The lifetime of Ural blocking is usually shorter than that of blackings over the two oceans. The reason is that there are two stable deep troughs in the upstream of blockings over the two oceans, and these troughs sustain the warm advection of maintaining blockings. While the Ural blocking has no such superiority compared with blockings over the two oceans, its lifetime span is less than that of the 30—60 day LFO. However, it is still a comparable stable blocking, which plays an important role in China's weather and climate.

Even if there is no such strong and stable upstream systems as the East Asian trough to provide warm advection, but in the upstream of Ural blocking there are still synoptic scale troughs which separate from the Iceland low. The warm advection ahead of troughs is one of the facilitating factors to the formation of Ural blocking.

Another factor is topography forcing. According to the recent research on the cold air damming (Xu et al. 1996), when west wind in the low level meets Ural Mountains, a northward jet parallel to the mountains emerges. This jet sucks more low-level flow and moves northward when it meets the mountains. It can be seen from ground wind field that the wind near the Ural turns northward in systematic way (Fig. 16).

Once the south wind in the low level couples the south wind ahead of the middle level trough, this kind of situation is quite favorable to the formation of Ural blocking

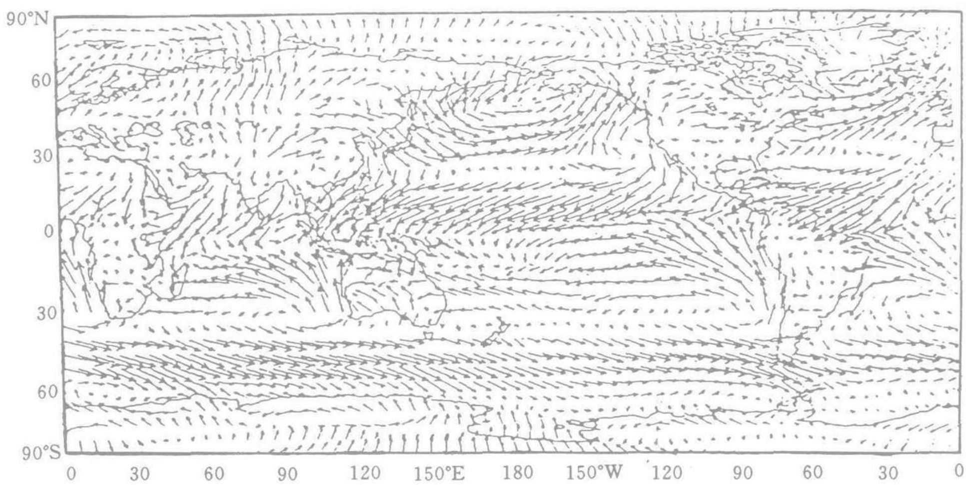

Fig. 16. Averaged wind field on 1000 hPa.

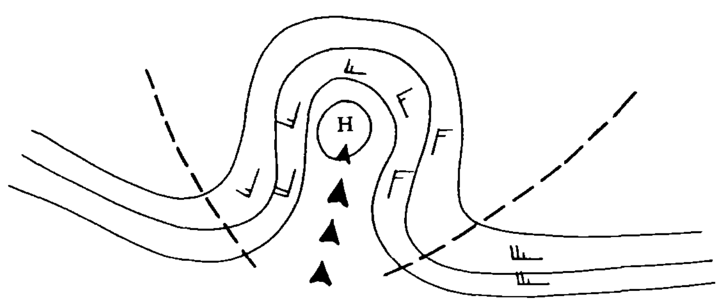

Fig. 17. Ural blocking pattern formed by low level wind of topography forcing coupling with warm advection ahead of the middle level trough (topography denoted by the black triangles).

(Fig. 17).

The topography forcing is a very important factor in the formation of Ural blocking. This point is different from the formation of blockings over the two oceans. Besides this. for the formation of Ural blocking. the topography drag or resonance and land-air interaction maybe also play some roles. but now their importance is lack of enough evidence.

The maintenance of the Ural blocking shows apparent wave-flow interaction. First. when the trough separating from the Iceland low moves eastward. and cold advection behind the trough is continuously complemented by cold air coming from Barents Sea. so that the trough can be persistently sustained. Because the south tip of the trough is located in the region of the polar front jet of westerlies. and has function of carrying waves. so the move speed of the south tip of the trough is faster than its north part. After some time. a Ω-pattern blocking is formed (Fig. 18).

However. the experience of weather forecasting verifies that if the cold advection

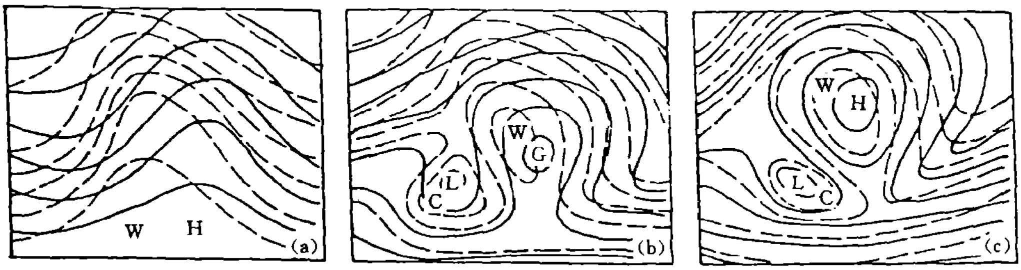

Fig. 18. The formation process of Ural blocking.

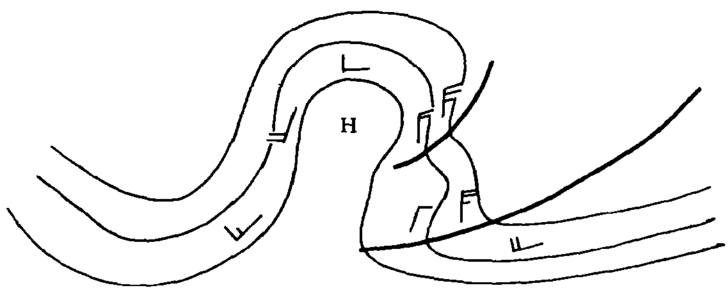

Fig. 19. The cold air glides into the transverse trough along the head of the blocking ridge.

coming from Barents Sea mismatches with the trough or inserts into the ahead of trough in advance. as a result, the trough becomes weak or because cold advection behind the trough is so strong that it makes the trough deepened to southward extension, the warm advection ahead of the trough is cut off so that the trough becomes unstable or collapses and Ural blocking as well. From the viewpoint of weather forecasting, for the Ural blocking formation, we should pay more attention to its upstream instead of the downstream. Usually saying "the turning of the transverse trough leads to the collapse of the blocking" is not of scientific significance. Saying "The collapse of the blocking and transverse trough turning" seems to be more reasonable. This is because that although the transverse trough located in the downstream of the blocking becomes stronger by the complement of cold air, the energy of transverse trough is continuously transported away by the westerly jet due to the trough located in the polar front jet region. The result is that many small troughs move eastward along the jet and carry a little cold air southward. so the transverse trough is persistently maintained. The real cause of transverse trough turning is due to the collapse of the blocking, which destroys the circulation situation maintaining the transverse trough. In the downstream of the blocking, the cold air from the east of the Novaya Zemlya Island continuously glides along the ridge of blocking into the transverse trough. Therefore, the small trough gliding along the head of the blocking ridge supplements energy to the transverse trough, and the more importance is to strengthen and maintain the circulation ahead of the blocking ridge. It is very favorable to the maintenance of the transverse trough and the blocking (Fig. 19).

Just because of this point, it is important for the prediction of the blocking to find whether there is cold air gliding along the head of the blocking ridge into the transverse trough.

In summary, the prediction of the blocking should focus on the upstream of the blocking. The collapse of the blocking needs to be analyzed from the match of the cold advection from the Barents Sea with the trough from the west. The maintenance of the blocking should be analyzed in view of the downstream of the blocking, that is, whether the cold air from the Kara Sea continuously replenishes the transverse trough along the head of the blocking ridge. The disposition of wave-flow interaction provides a significant clue to predicting of variation of the Ural blocking.

IV. SOME DISCUSSIONS AND CONCLUSIONS

Based on the review of the some previous researches and through comparison between the observational facts and diagnostic analyses, and combining them with long-time experience of weather prediction, some opinions and researches on the formation and maintenance of blockings are proposed. They provide not only some facts for further theoretical study, but also some clues and ideas for the prediction of the formation, maintenance and collapse of blockings. Many meteorologists all over the world concern and do research on the LFO of blocking pattern, they have proposed many formation mechanisms of the blocking, such as water-like jump and resonance, soliton and dipole, linear and nonlinear instability and multi-equilibria, and so on. The problem is which theory is closest to the real situation? Which theory is based on the observational analysis and diagnoses? And which theory can be used to guide the weather forecasting and is consistent with the forecaster's experience. These questions are still difficult to answer. The value of this paper lies in providing some results of observational facts and diagnostic analyses for the further theoretical study.

Bengtsson (1996) summarized the blocking formation from the viewpoint of numerical simulation. He proposed that the formation mechanism of blockings over Atlantic and Europe is related to the local nonlinear instability of the transient eddy which can produce the free dipole, while the normal model instability of the 3-dimensional basic flow is responsible for the formation of the blocking over the Pacific. His opinion about the Pacific blocking formation is similar to ours. The instability of the 3-dimensional basic flow is the instability of the flow, which is mainly caused by nonlinear thermal advection and SST heat forcing. We are different from Bengtsson that we also think the normal model instability of the 3-dimensional basic flow as the formation mechanisms of blocking over the Atlantic. However, we have the same opinion about the formation of Ural blocking, because the upstream of the Ural blocking is supported by the trough separated from the Iceland low, which basically belongs to the transient wave, and its south tip locates in the jet region and moves faster than its north part, not only the Ω-pattern blocking is formed (Fig. 18), but also forms the blocking dipoles when trailing trough becomes leading trough and then coheres with the transverse trough ahead of the blocking anticyclonically. So the formation of Ural blocking maybe links with the local nonlinear instability of the basic flow, which can result in the dipole-like transient wave. Besides this, Ural Mountains also play an important role in the formation of the blocking. Therefore if some dynamical processes need to be done, it is necessary to consider the effect of Ural Mountains.

Finally, it should be pointed out that the low-frequency anomalies of blocking pattern are related to the heat forcing of oceans and dynamic forcing of topography, and the low boundary forcing impacts the middle and low-level atmosphere through the variation of the elements in the boundary layer. The problems of the boundary layer in the low-frequency variation of blocking pattern are intriguing issues.

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